Particle Spectrum in Supersymmetric Models with a Gauge Singlet

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Abstract:
We scan the complete parameter space of the supersymmetric standard model extended by a gauge singlet, which is compatible with the following constraints: universal soft supersymmetry breaking terms at the GUT scale, finite running Yukawa couplings up to the GUT scale and present experimental bounds on all sparticles, Higgs scalar and top quark. The full radiative corrections to the Higgs potential due to the top/stop sector are included. We find a lower limit on the gluino mass of 160 GeV, upper limits on the lightest neutral scalar Higgs mass dependent on $m_{\text{top}}$ and the size of the soft supersymmetry breaking terms, and the possibility of a Higgs scalar as light as 10 GeV, but with reduced couplings to the Z boson.

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The main task of present and future accelerators is the search for the Higgs boson, the top quark and, if existent, the new particles predicted by supersymmetry. Predictions on the particle spectrum in supersymmetric models can, however, only be made under additional assumptions: One can invoke some conditions on the absence of fine tuning, one can assume the running Yukawa couplings not to diverge below a GUT scale, and one can make assumptions on the parameters specifying the soft supersymmetry breaking terms (the gaugino masses, the masses of the scalars and the trilinear couplings among the scalars).

Most of the recent discussions of the allowed space of parameters and the particle spectrum, under various of the above assumptions, have appeared within the minimal supersymmetric extension of the standard model (MSSM) \[1\]-[8]. Also most of the experimental analyses have been done in the framework of the MSSM. There the Higgs sector is specified by just two unknown parameters, which include a supersymmetric mass term $\mu$ for the two Higgs doublets. This $\mu$ - term is actually a nuisance, since an explanation of its presence and a reason, why it should be of the same order of magnitude as the soft susy breakings, requires additional assumptions like radiative corrections involving a GUT sector [9], nonrenormalizable interactions within supergravity [10], [11], nontrivial Kähler potentials [12] or accidental global symmetries in the superpotential [13].

It is important, however, to extend theoretical and experimental studies beyond the MSSM and consider supersymmetric extensions such as the one involving one gauge singlet ((M+1)SSM) [14]-[18]. For instance, the upper bound on the lightest Higgs boson mass within the MSSM is violated already in this (M+1)SSM. Furthermore the $\mu$ - term can be omitted, and the entire superpotential can be chosen to be scale invariant, i.e. to include only dimensionless Yukawa couplings, by imposing a discrete $Z_3$-symmetry. This is also the typical structure emerging from superstring motivated scenarios.

Under the assumption of a scale invariant superpotential and universal soft susy breakings at the GUT scale the Higgs sector of the this model involves five independent parameters, two Yukawa couplings in the superpotential and three universal soft susy breakings at the GUT scale. Due to the importance of the top/stop induced radiative corrections (renormalization effects from the GUT scale down to the electroweak scale as well as radiative corrections to the Higgs potential) the top Yukawa coupling appears as a sixth important parameter. On the other hand the knowledge of the $Z/W$ masses reduces the number of unknown parameters again to five.

Some investigations of the parameter space of the (M+1)SSM have been performed in [16]. If universality at the GUT scale was assumed, however, the authors confined themselves to soft susy breaking triggered by gaugino masses only. Recently upper bounds on the mass of the lightest neutral Higgs scalar under the only assumption of the absence of fine tuning [19] or finite running Yukawa couplings below $M_{GUT}$ have been the subject of detailed investigations [20]-[30].

A scan of the complete five dimensional parameter space assuming universal soft susy breakings at $M_{GUT}$ and hence $SU(2) \times U(1)$ symmetry breaking triggered by radiative corrections, providing a stable vacuum and respecting the present ex-
experimental constraints, is substantially more involved and is the task of the present paper as well as a forthcoming publication \cite{31}. It is not even clear, a priori, whether all conditions can be satisfied simultaneously, and whether the previously derived bounds can be saturated under these additional conditions.

Let us describe the model and our procedure. The relevant part of the superpotential has the form

$$ W = h_t Q \cdot H_2 T_R^c + \lambda H_1 \cdot H_2 S + \frac{1}{3} \kappa S^3 $$ \hspace{1cm} (1)

where colour indices are suppressed and

$$ Q = \begin{pmatrix} T_L \\ B_L \end{pmatrix}, \quad H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}, \quad Q \cdot H = Q_i \epsilon^i j H_j \text{ etc.} $$ \hspace{1cm} (2)

The scalar potential contains the standard $F$- and $D$-terms, the soft susy breaking terms and in addition the one loop radiative correction of the form

$$ V^{rad} = \frac{1}{64 \pi^2} \text{Str}[M^4 \ln(M^2/Q^2)]. $$ \hspace{1cm} (3)

The soft supersymmetry breaking gaugino masses, trilinear couplings and scalar masses are given by

$$ (\mu_1 \lambda_1 \lambda_1 + \mu_2 \lambda_2 \lambda_2 + \mu_3 \lambda_3 \lambda_3 + h_t A_t Q \cdot H_2 T_R^c + \lambda A \lambda H_1 \cdot H_2 S + \frac{1}{3} \kappa A \kappa S^3) + \text{ h.c.} $$

$$ + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_3^2 |S|^2 + m_Q^2 |Q|^2 + m_T^2 |T_R^c|^2 + ... $$ \hspace{1cm} (4)

where $\lambda_1$, $\lambda_2$ and $\lambda_3$ denote the gauginos of the $U(1)_Y$, $SU(2)$ and $SU(3)$ gauge groups respectively.

Concerning the radiative corrections (3) we only take top quark and squark loops into account. The corresponding bottom contributions are negligible assuming $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle < 20$, and the gauge sector is known to play no important role \cite{32, 33}. This also holds for the extended Higgs sector, since the Yukawa couplings $\lambda$ and $\kappa$ will turn out to be small. Indeed, we eventually find $\lambda^2 < g_2^2$, where $g_2$ is the $SU(2)$ gauge coupling, a sufficient condition to forbid the breaking of electromagnetism in the Higgs sector \cite{34}. It has also been shown that supersymmetry prevents the spontaneous breaking of $CP$ \cite{35}, so that the vevs of the fields $H_1, H_2$ and $S$ are of the form

$$ \langle H_1 \rangle = \begin{pmatrix} h_1 \\ 0 \end{pmatrix}, \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ h_2 \end{pmatrix}, \quad \langle S \rangle = s $$ \hspace{1cm} (5)

with $h_1$, $h_2$ and $s$ real. The Higgs vev dependent top quark mass appearing in (3) is given by

$$ m_t = h_t h_2 $$ \hspace{1cm} (6)

and the top squark mass matrix, in the basis $(T_R^c, T_L^c)$, by

$$ \begin{pmatrix}
 h_t^2 h_2^2 + m_T^2 - \frac{g_2^2}{3}(h_2^2 - h_1^2) & h_t(A_t h_2 + \lambda sh_1) \\
 h_t(A_t h_2 + \lambda sh_1) & h_t^2 h_2^2 + m_Q^2 + (\frac{g_1^2}{12} - \frac{g_2^2}{4})(h_2^2 - h_1^2)
\end{pmatrix}. $$ \hspace{1cm} (7)
The equations for extrema of the full scalar potential in the directions (5) in field space read

\[ h_1[m_1^2 + \lambda^2(h_2^2 + s^2) + \frac{g_1^2 + g_2^2}{4}(h_1^2 - h_2^2)] + \lambda h_2 s(\kappa s + A_\lambda) + \frac{1}{2} \partial V^{\text{rad}}/\partial h_1 = 0, \quad (8) \]

\[ h_2[m_2^2 + \lambda^2(h_1^2 + s^2) + \frac{g_1^2 + g_2^2}{4}(h_2^2 - h_1^2)] + \lambda h_1 s(\kappa s + A_\lambda) + \frac{1}{2} \partial V^{\text{rad}}/\partial h_2 = 0, \quad (9) \]

\[ s[m_3^2 + \lambda^2(\hbar_1^2 + \hbar_2^2) + 2\kappa^2 s^2 + 2\lambda h_1 h_2 + \kappa A_\kappa s] + \lambda A_\lambda h_1 h_2 + \frac{1}{2} \partial V^{\text{rad}}/\partial s = 0. \quad (10) \]

In order to implement the assumption of finite Yukawa couplings up to \(10^{16}\) GeV and universal soft susy breakings at \(10^{16}\) GeV we need the renormalization group equations for \(\lambda, \kappa\) and \(h_t\) and the susy breakings \(m_1^2, m_2^2, m_3^2, m_0^2, m_7^2, A_\lambda, A_\kappa\) and \(A_t\). These can be found in \([15],[16]\).

We scan the parameter space of the model as follows: First we fix \(\sim 3000\) different combinations of the Yukawa couplings \(\lambda_0, \kappa_0\) and \(h_{0t}\) at the GUT scale in the range from 0 to 3. In each case we integrate the renormalization group equations numerically down to the electroweak scale of \(O(100)\) GeV. Thereby we determine the "low energy" Yukawa couplings \(\lambda, \kappa\) and \(h_t\) as well as the coefficients of the expansion of the "low energy" susy breakings \(m_1^2, \ldots, A_t\) in terms of the three bare susy breakings \(\mu_0, A_0\) and \(m_0^2\):

\[ m_i^2 = a_i \mu_0^2 + b_i A_0^2 + c_i \mu_0 A_0 + d_i m_0^2, \quad i = 1, 2, S, Q, T; \]

\[ A_a = e_a A_0 + f_a \mu_0, \quad a = t, \lambda, \kappa. \quad (11) \]

The coefficients \(a_i, \ldots, f_a\) are completely specified by the three Yukawa couplings and the gauge couplings and are computed numerically. Next, in each case, we scan over \(\sim 5000\) different values of the singlet vev \(s\) and \(\tan \beta\) with

\[ 0 < s < 10 \quad \text{TeV}, \]

\[ 1 < |\tan \beta| < 20. \quad (12) \]

In each of those \(\sim 15 \times 10^6\) cases, we insert the specified values for all three vevs \(h_1, h_2\) and \(s\) together with the expansions (11) into the minimization equations (8 - 10). These allow us to compute the three high energy susy breakings \(\mu_0, m_0^2\) and \(A_0\).

Having fixed all parameters of the low energy potential we next check, whether the present choice of vevs corresponds to an absolute minimum of the potential. Thus we compute the energy density and compare it with the extrema of the potential where either \(h_1, h_2\) or \(s\) vanishes. Large values of the trilinear couplings can induce squark or slepton vevs, which would break color and/or electromagnetism \([37],[13],[18]\). The most dangerous possibility turns out to be \(U(1)_{\text{e.m.}}\) breaking by a selectron vev, against which we check after having computed the required trilinear coupling and slepton masses and imposing the condition

\[ A_E^2 < 3(m_E^2 + m_L^2 + m_1^2) \quad (13) \]
In the remaining cases we proceed to calculate the physical masses of the particles (their expressions in terms of the low energy parameters are given in the literature [16], [17], [19]). In addition we compute the masses of the selectrons, sneutrino, top quark, top squarks, gluino as well as the coupling of the lightest neutral Higgs scalar to the Z boson. Then we impose the following experimental constraints: We demand the sparticles which could be pair produced in \(Z_0\) decay (selectrons, sneutrino, squarks, charged Higgs scalar and charginos) to be heavier than 45 GeV, the gluino to be heavier than 110 GeV, the top quark to be heavier than 110 GeV and the lightest neutral Higgs scalar either to be heavier than 58 GeV or to have a reduced coupling to the Z boson according to a recent analysis of the LEP experiments, which is general enough to include extensions of the MSSM as the present one [39].

At the end we are still left with a considerable range of parameters and masses, which satisfy all the constraints. The complete range of Yukawa couplings, soft susy breakings, \(s\) and \(\tan \beta\) found by our procedure is given by

\[
0 < \lambda_0 < .55 \\
0 < \kappa_0 < .65 \\
.25 < h_{t0} < 3 \\
60 \text{ GeV} < |\mu_0| < 4 \text{ TeV} \\
0 < m_0 < 3.5 \text{ TeV} \\
25 \text{ GeV} < |A_0| < 10 \text{ TeV} \\
800 \text{ GeV} < s < 10 \text{ TeV} \\
2 < |\tan \beta| < 20. \tag{14}
\]

The lower limit on \(h_{t0}\) is a reflection of our lower bound on \(m_{\text{top}}\) of 110 GeV. The nonvanishing lower limit on \(A_0\) indicates that a scenario with gaugino masses as the only source of susy breaking is not allowed. (This limit is due to the present experimental constraints on the lightest neutral Higgs scalar.) A striking feature of these solutions is the large vev of the singlet \(s\) with respect to the weak interaction scale. As a matter of fact the upper limits on the susy breakings are not genuine, but a reflection of our upper limit (12) on \(s\). At low energies the Yukawa couplings vary, as implied by (14), between 0 and .4 in the case of \(\lambda\) and \(\kappa\), and between .7 and 1.1 in the case of \(h_t\).

In view of the large values of \(s\) that characterise the solutions, it is possible to understand some features of the results in terms of approximate analytic solutions of the minimization equations (8) - (10) and the RG equations. In the limit \(s^2 >> h_1^2 + h_2^2 = (174 GeV)^2\) the stable solutions of (10) are given by the relations

\[
4 \kappa s = -A_\kappa + \sqrt{A_\kappa^2 - 8m_S^2} \\
A_\kappa^2 > 8m_S^2 \tag{15}
\]

As a matter of fact, with \(s\) given by (15), eqs. (8) and (9) are close to the minimum conditions in the MSSM with the usual parameters \(B\) and \(\mu\) given by

\[
B = A_\lambda - \kappa s, \quad \mu = \lambda s. \tag{16}
\]
It has to be noticed, however, that here the spectrum is richer and the deviations from the MSSM physically relevant. Only in the mathematical limit \( s \to \infty; \lambda, \kappa \to 0 \) with \( \lambda_s, \kappa_s \) fixed the MSSM is reproduced.

To proceed let us make another approximation and neglect terms of \( O(\kappa^2/h_t^2, \lambda^2/h_t^2) \) in the RG equations of the Yukawa couplings and soft breaking terms. From the solutions of the RGEs analogous to those given in [40] one can easily infer the low energy Yukawa couplings and soft terms to \( O(\kappa^2/h_t^2, \lambda^2/h_t^2) \) in terms of the high energy ones. They turn out to be as follows:

\[
\begin{align*}
\kappa^2 &\approx \kappa_0^2 \\
\lambda^2 &\approx 1.86\lambda_0^2(1 - .822h_t^2)^{1/2} \\
A_\lambda &\approx A_0(1 - .411h_t^2) - \mu_0(.59 - .86h_t^2) \\
A_\kappa &\approx A_0 \\
m_\lambda^2 &\approx m_0^2 \\
m_\tau^2 &\approx m_0^2 + .53\mu_0^2 \\
m_2^2 &\approx m_0^2(1 - 1.644h_t^2) + .53\mu_0^2 - 3h_t^2[.137A_0^2(1 - .822h_t^2) \\
&\quad + .56A_0\mu_0(1 - .822h_t^2) + \mu_0^2(1.65 - .50h_t^2)] \
\end{align*}
\]

(17)

(see [31] for details). Thus in the small \( \kappa, \lambda \) approximation the condition on \( A_\kappa \) in (15) gives

\[
A_0^2 > 8m_0^2.
\]

(18)

At this stage we must check against colour and/or electromagnetism breaking solutions. From expressions analogous to (17) we find the parameters of (13) calculated at a scale of \( O(A_E/h_e) \sim 10^8 \) GeV, hence the condition (13) can be translated into the following condition on the parameters at the GUT scale in the limit of small \( \kappa, \lambda \):

\[
A_0 < .4\mu_0 + \sqrt{9m_0^2 + 2\mu_0}
\]

(19)

The approximations involved in (17) - (19) improve as \( \lambda, \kappa \to 0 \) with \( \lambda_s, \kappa_s \) fixed. Therefore, the (M+1)SSM includes the MSSM as a limiting case, but with a further restriction on the parameters as given by these relations, at least under the assumption of universality of the soft terms at the unification scale. But even if this assumption is given up, eq.(15), that follows from (10) in this limit, provides a restriction in the resulting MSSM, whatever the boundary conditions at high energies may be.

For larger values of \( \kappa, \lambda \) the corresponding values for the soft parameters increase and the overall solutions may require some degree of finetuning of \( A_0, \mu_0 \) and \( m_0^2 \). We looked for correlations among these parameters (at fixed Yukawa couplings), but found only a relatively weak one among \( m_0 \) and \( A_0 \) of the form

\[
A_0 \sim 3m_0 \pm 1 \text{ TeV.}
\]

(20)

The essential features of the particle spectrum are as follows: The top quark mass is bounded from above by 190 GeV, which is a well known consequence of a
finite value of $h_{t0}$. There are no obvious correlations between the top quark mass and the scale of susy breaking.

For the mass of the lightest neutral Higgs scalar we obtain an upper bound depending on $m_{t_{\text{top}}}$ and the soft susy breakings $A_t$, $m_Q$ and $m_T$. Here the complete radiative corrections induced by $V^{\text{rad}}$ of eq. (4) are seen to play an important role: For $m_{t_{\text{top}}} \approx 190$ GeV and $A_t$, $m_Q$ and $m_T \gtrsim 2$ TeV we have cases where the tree level part of the Higgs potential would suggest a mass of the lightest neutral Higgs scalar of $\sim M_Z$, the effect of the leading logarithms of the form $\sim \ln (m_{\text{stop}}^2/m_{t_{\text{top}}}^2)$ increase it to $\sim 145$ GeV, and the remaining corrections to the Higgs potential as computed in [27]-[30] increase it to $\sim 155$ GeV. This value constitutes an upper bound on $M_H$ for the range (14) of the soft susy breakings; if, instead, we assume upper limits on $A_t$ or $m_{\text{stop}}$ of $\sim 1$ TeV, this upper bound decreases to $\sim 140$ GeV. In fig.(1) we plot the bound on $M_H$, for the different ranges of the soft susy breakings, versus $m_{t_{\text{top}}}$. We also plot the bound based solely on the assumption of perturbative Yukawa couplings below $M_{\text{GUT}}$ within this model (again with upper limits on $A_t$ or $m_{\text{stop}}$ of $\sim 1$ TeV, taken from [28]). This shows the decrease of the upper bound, mainly at moderate values of $m_{t_{\text{top}}}$, due to the additional assumption of universal soft susy breakings. It is related to the fact that we found an upper limit on the Yukawa coupling $\lambda_t$ (see eq. (14)).

In the case of light neutral Higgs scalars we find the interesting possibility that this particle could contain a large admixture of the gauge singlet field $S$, and hence have a substantially reduced or even vanishing coupling to the Z boson. (This possibility has also been observed in [16], [26].) It allows Higgs masses as light as 10 GeV to be compatible with up to date unsuccessful Higgs searches. This feature persists up to Higgs masses of $\sim 100$ GeV, whereas for Higgs masses beyond 125 GeV its coupling to the Z boson has to be very close to the one of the standard model Higgs boson.

Concerning the charged Higgs scalar, charginos, stops and sleptons we find that each of them could be as light as 45 GeV and thus be detectable in the near future. However, the combination of the experimental lower bounds on these particle masses results in the lower limit of $\sim 60$ GeV on the bare susy breaking gaugino mass term $\mu_0$, which implies a lower bound on the gluino mass of $\sim 160$ GeV. The finding of a lighter gluino would thus imply a violation of our underlying assumption of universality.

As is clear from the possible range of susy breakings, all new particles implied by supersymmetry are also allowed to be very heavy; upper limits on their masses can be obtained invoking some condition on the absence of fine tuning, which is not the purpose of the present paper.

Our procedure allows us to study a multitude of correlations among these masses. In fig.(2) we plot the allowed range of the masses of the lightest chargino and the lightest top squark versus the gluino mass. This plot explicitly shows the common increase of the sparticle masses, but also how difficult it is to deduce one mass from the other below 1 TeV under our general assumptions. More correlations will be discussed in a separate more extended paper [31].

In conclusion, we have shown that the supersymmetric extension of the stan-
standard model involving a gauge singlet, and assuming universal susy breakings at the GUT scale, can well satisfy all present experimental constraints. A scenario with the gaugino mass as the only seed of soft susy breaking at $10^{16}$ GeV is, however, excluded. A gluino below 160 GeV is not allowed within this model. For moderate soft susy breakings (below 1 TeV) the upper bound on the lightest neutral Higgs scalar varies between 100 GeV for $m_{\text{top}} = 100$ GeV and 140 GeV for $m_{\text{top}} = 190$ GeV. The possibility of a light Higgs scalar with reduced couplings to the Z boson leads to interesting tasks for experiments. Clearly our procedure will allow us to make more refined predictions as soon as more experimental information (e.g. on $m_{\text{top}}$) is available, or if theoretical assumptions on the soft susy breakings or on the Yukawa couplings are made.
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**Figure Captions**

Fig. 1: Upper bound on the mass of the lightest neutral Higgs scalar versus $m_{top}$. Full line: result for the range (18) of the soft susy breakings, dashed line: result with upper limits on $A_t$ or $m_{stop}$ of $\sim 1$ TeV, dotted line: result with upper limits on $A_t$ or $m_{stop}$ of $\sim 1$ TeV, taken from [28].

Fig. 2: Allowed range of the masses of the lightest chargino (within the full lines) and the lightest top squark (within the dashed lines) versus the gluino mass.