CONSTRAINTS ON THE MINIMAL SUSY SO(10) MODEL
FROM COSMOLOGY AND THE $b \rightarrow s\gamma$ DECAY

F.M. Borzumati$^{1,2)}$, M. Olechowski$^{3)}$ and S. Pokorski$^{4)}$*

$^1)$ II. Institut für Theoretische Physik
Universität Hamburg, 22761 Hamburg, Germany

$^2)$ Department of Theoretical Physics
Technischen Universität München, 85747 Garching, Germany

$^3)$ Theory Division, CERN, 1211 Genève 23, Switzerland

$^4)$ Max-Planck Institute for Physics
Föhringer Ring 6, 80805 Munich, Germany

Abstract

It is shown that the minimal supersymmetric SO(10) model with electroweak radiative breaking and universal soft mass terms at the GUT scale is strongly disfavoured by the combination of constraints from the $b \rightarrow s\gamma$ decay and the condition $\Omega h^2 < 1$ for the lightest (stable) neutralino. The constraints are, however, easily satisfied for certain class of supersymmetric SO(10) models with non–universal scalar masses which gives small supersymmetric corrections to the bottom quark mass and light higgsino–like neutralinos.
In the minimal supersymmetric SO(10) (SUSY–SO(10)) models the Yukawa couplings of the tau lepton and of the bottom and top quarks unify at the scale of grand unification. The consequence of such an exact unification of couplings is that the top quark mass, \( m_t \), and the ratio of the two vacuum expectation values present in the model, \( \tan \beta \), are determined, once the bottom quark mass, \( m_b \), the tau lepton mass, \( m_\tau \), and the strong gauge coupling, \( \alpha_S \), are fixed [1, 2, 3]. Large values of \( \tan \beta \) are naturally obtained in this case, leading to a proper bottom–top mass hierarchy [4].

In this context, an interesting question is the issue of the compatibility of this exact Yukawa coupling unification with the possibility of breaking the electroweak gauge symmetry through radiative effects. This question has been investigated in a number of papers in the minimal SUSY–SO(10) models with universal [5, 2] and non–universal [6, 7] soft supersymmetry breaking parameters at the GUT scale. Moreover, it has been recently observed that for these large values of \( \tan \beta \), potentially large corrections to \( m_b \) may be induced through the supersymmetry breaking sector of the theory [3, 2]. These corrections are decisive in obtaining acceptable predictions for \( m_t \), when the supersymmetric parameter space is constrained by the mechanism of radiative breaking.

A systematic and complete determination of the GUT scale parameter space of the minimal SUSY–SO(10) models with universal soft breaking terms has been carried out in [2]. The approach used in this study is the bottom–up approach discussed in [8]. It was found that the requirement of radiative electroweak breaking implies strong correlations between the soft supersymmetry breaking parameters and, as a consequence, distinct features of the sparticle spectrum. In addition, the supersymmetry corrections to \( m_b \) were found to be almost constant for fixed \( \tan \beta \) and to imply an upper bound on \( m_t \) of the order of (160–170) GeV. A study of SUSY–SO(10) models with non-universal boundary values for the soft breaking terms, which uses the same bottom-up approach, was performed in [5].

This work is a supplement to the studies presented in [2, 4]. We investigate here the constraints due to the requirement that the relic abundance of the lightest neutralino, which is the lightest supersymmetric particle (LSP) in these models, does not overclose the Universe. Furthermore, we study the restrictions imposed by the recent observation of the inclusive decay \( b \rightarrow s\gamma \) by the CLEO II Collaboration [9]. The measured branching ratio has the value:

\[
\text{BR}(b \rightarrow s\gamma) = (2.32 \pm 0.51 \pm 0.29 \pm 0.32) \cdot 10^{-4},
\]

where the errors are statistical, experimental systematics and theoretical systematics (due to the extrapolation from the observed part of the photon spectrum). This measurement implies a 95% c.l. upper and lower limits on this branching ratio of \( 3.4 \cdot 10^{-4} \) and \( 1.2 \cdot 10^{-4} \), respectively [10]. Both constraints turn out to be important for SUSY–SO(10) models, given the correlations present in their parameter spaces.

We start our discussion with the SUSY–SO(10) model with universal soft breaking terms. In order to set the terms of our discussion, we give a brief summary of the main properties of the parameter space and of the spectra characteristic of this model. We list
here the properties which are relevant for our present results and we refer to \cite{2} for further details.

The requirement of radiative electroweak breaking with $\tan \beta \approx m_t / m_b$ implies the following correlations on the GUT scale parameters:

$$M_{1/2} \geq \mathcal{O}(300 \text{ GeV}); \quad \mu \simeq (1.5 - 1.7) M_{1/2}; \quad M_{1/2} > m_o.$$  \hspace{1cm} (2)

where $M_{1/2}$ and $m_o$ are the common gaugino and scalar masses, and $\mu$ is the Higgs doublet mixing parameter present in the superpotential. As it is well known, the renormalization group equations (RGE) relate the gaugino mass at $M_Z$, $M_{2}$, and the gluino mass, $M_{\tilde{g}}$, to the GUT scale gaugino mass, as in the following: $M_{2} \approx M_{1/2}$ and $M_{\tilde{g}} \approx 3M_{1/2}$.

It is clear that the relation (2) has immediate consequences on the nature and the possible values of masses of charginos and neutralinos. The lightest neutralino, $\tilde{\chi}^0_1$, and lightest chargino, $\tilde{\chi}^+_{1,2}$, are almost purely gaugino-like. Their masses, related by a factor of two (the charged particle being the heavier) are bounded from below:

$$m_{\tilde{\chi}^+_1} \approx 0.5 m_{\tilde{\chi}^+_{2,3}} \approx 0.5 M_{2} \geq 100 \text{ GeV}.$$  \hspace{1cm} (3)

Moreover, the mass of the pseudoscalar Higgs boson $A$ at the scale $M_Z$, turns out to be bounded from above by the low-energy mass parameter entering the chargino mass matrix, $M_{2}$, :

$$m_A^2 < O(0.1) M_{2}^2$$  \hspace{1cm} (4)

where the coefficient $O(0.1)$ follows from the RGE. Thus, the mass of the pseudoscalar Higgs boson $A$ is smaller than the mass of the lighter chargino: $m_A < m_{\tilde{\chi}^+_{1,2}} \approx 2m_{\tilde{\chi}^0_1}$.

As an illustration, we show in Fig. 1a the values of $m_A$ versus $m_{\tilde{\chi}^+_{1,2}}$ obtained for $m_t = 160 \text{ GeV}$ and $\tan \beta = 40$ with a scanning of the squark masses within the range $150 \text{ GeV} < m_{\tilde{q}} < 2 \text{ TeV}$. In Fig. 1b we show the higgsino component $Z_{13}$ of the lightest neutralino defined by the decomposition

$$\tilde{\chi}^0_1 = Z_{11} \tilde{B} + Z_{12} \tilde{W} + Z_{13} \tilde{H}_1 + Z_{14} \tilde{H}_2.$$  \hspace{1cm} (5)

The $Z_{14}$ component turns out to be roughly a factor 3 smaller. The higgsino components of $\tilde{\chi}^0_1$ decrease with the ratio $M_W/(M_1 - \mu)$.

The supersymmetric correction to the bottom quark mass in SUSY-SO(10) models reads \cite{3, 4}

$$\Delta(m_b) = \frac{\tan \beta}{4\pi} \left\{ \frac{8}{3} \alpha_S M_{\tilde{g}} \mu I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, M_{\tilde{g}}^2) + Y_t \mu A_t I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2) \right\},$$  \hspace{1cm} (6)

where the function $I(a, b, c)$ is listed in \cite{3}; $m_{\tilde{b}_i}$ and $m_{\tilde{t}_i}$, with $i = 1, 2$ are sbottom and stop masses; and $A_t$ is the trilinear soft breaking term for the top quark at the low-energy scale $M_Z$. The RGE with large top and bottom quark Yukawa couplings provide a relation between $A_t$ and $M_{\tilde{g}}$:

$$A_t \simeq -M_{\tilde{g}}$$  \hspace{1cm} (7)

and also give

$$m_{\tilde{g}}^2 \simeq O(5) M_{1/2}^2.$$

P: 2
Those relations, together with eq. (2), imply that the supersymmetric correction to the bottom quark mass is large, generically $O(20\% - 30\%)$, and almost constant for fixed $\tan \beta$.

Since the final value of the bottom quark pole mass should be in the experimental range $m_b = (4.9 \pm 0.3)$ GeV the mass before supersymmetric corrections must be either small or large enough to accomodate those large corrections. The first option is inconsistent with Yukawa and gauge coupling unification [3, 2] and, therefore, the supersymmetric correction (5) must be negative, i.e. the parameter space is further constrained by the requirement $\mu M_{1/2} < 0$ ($\mu A_t > 0$).

We can now discuss experimental constraints on the version of the model with universal boundary conditions coming from BR($b \rightarrow s\gamma$) and from the requirement that the neutralino relic abundance satisfies $\Omega h^2 < 1$. Our numerical calculation is based on the formalism developed in ref. [12] for $b \rightarrow s\gamma$ and in ref. [13] for the neutralino relic abundance. As a representative example, we have taken $m_t = 160$ GeV and $\tan \beta = 40$ which give $m_b = 6.1$ GeV (before susy corrections) for $\alpha_s = 0.129$. We would like to stress that our conclusions are general and equally valid for the whole range of values of $m_t$, $\tan \beta$ and $\alpha_s$ consistent with the gauge and Yukawa coupling unification and specified in ref.[2].

The numerical results can be qualitatively understood in terms of the summarized above properties (2,3,5) of the parameter space and the spectra. For large $\tan \beta$, the dominant contribution to the $b \rightarrow s\gamma$ decay rate (additional to the standard model one) comes from the charged Higgs and chargino exchanges. We can estimate them by using the formulae of ref. [12] in the approximation of no mixing between the gaugino and higgsino and in the limit of large $\tan \beta$: 

$$A_{H^+} \approx \frac{1}{2} \frac{m_t^2}{m_{H^+}^2} f^{(2)} \left( \frac{m_t^2}{m_{H^+}^2} \right),$$

$$A_{\tilde{\chi}^+} \approx -\frac{\tan \beta}{4} \frac{m_t}{\mu} \left[ f^{(3)} \left( \frac{m_{\tilde{\chi}^+}^2}{\mu^2} \right) - f^{(3)} \left( \frac{m_{\tilde{\chi}^0}^2}{\mu^2} \right) \right]$$

where

$$f^{(2)}(x) = \frac{3 - 5x}{6(x - 1)^2} + \frac{3x - 2}{3(x - 1)^2} \ln x,$$

$$f^{(3)}(x) = \frac{7x - 5}{6(x - 1)^2} - \frac{x(3x - 2)}{3(x - 1)^3} \ln x$$

and $m_{\tilde{\chi}^k}$ are the eigenvalues of the top squark mass matrix. One can check that for $m_t = m_{H^+} = 2M_W$, the charged Higgs contribution is equal to the Standard Model $W$ exchange contribution. The chargino contribution for the parameter space consistent with radiative electroweak breaking and the $SO(10)$ unification is mainly due to the exchange of the heavier (higgsino–like) chargino. The relative sign of the $H^+$ and $\tilde{\chi}^+$ contributions depends on the sign of the product $\mu A_t$ and is positive for $\mu A_t > 0$. We recall that the latter is required for a proper correction to $m_b$. It is also interesting to observe that $\tilde{\chi}^+$ contribution, although dominated by the $\tilde{\chi}_1^+$ exchange, is to a very good

---

1We use conventions of ref.[1]
approximation a unique function of $M_2$, i.e. of $m_{\tilde{\chi}^+}$. This is due to the strong linear correlation between $\mu$, $A_t$ and $M_2$: in general the chargino contribution depends on the stop mass (which in turn depends on $M_{1/2}$, $A_0$ and (only weakly) on $m_0$) and on the two chargino masses but in the parameter space constrained by radiative electroweak breaking it can be effectively parametrized only by the dependence on $m_{\tilde{\chi}^+}$. Finally, we note that the chargino contribution remains large for relatively heavy charginos and decreases with increasing $m_{\tilde{\chi}^+}$. This can also be understood from eq. (3).

The final results for the BR($b \to s\gamma$) are shown in Fig. 2 as a function of $m_{H^+}$. For given $m_{H^+}$ the branching ratio is bounded from below by the charged Higgs contribution (with negligible chargino contribution for heavy charginos) and from above by the sum of the $H^+$ and $\tilde{\chi}^+$ contributions, with the latter being maximal for $m_{\tilde{\chi}^+}$ at its lower bound shown in Fig. 1a. Thus, the experimental result (1) puts a strong lower limit on the mass of the charged Higgs and, in consequence, due to eq. (3) shown in Fig. 1a. Thus, the experimental result (1) puts a strong lower limit on the mass of the charged Higgs and, in consequence, due to eq. (3) ($m_{H^\pm} \approx m_A$), also on $M_2$. The bound shown in Fig. 2 for the $b \to s\gamma$ rate includes the theoretical uncertainties in the computation of the rate following the estimation of ref. [14], $BR^{\text{theor}}(B \to X_s\gamma) \pm \epsilon$, where $\epsilon$ is the theoretical error bar [14].

The annihilation of the lightest neutralino which, due to the relation (3), is strongly bino–like proceeds dominantly through s–channel CP odd Higgs exchange, whose coupling to $\tau\tau$ and $b\bar{b}$ is strongly enhanced for large $\tan \beta$. The dominant part of the $\chi^0_1A$ coupling is proportional to the product $Z_{11}Z_{13}$, with $Z_{11} \sim 1$ and $Z_{13}$ given in Fig. 1b. $\Omega h^2$ is an increasing function of $m_{\tilde{\chi}^0}$ since the relic mass is proportional to $m_{\chi^0}$ and the $Z_{13}$ coupling behaves as $Z_{13} \sim 1/m_{\chi^0}$. In addition, in the parameter space constrained by radiative electroweak breaking, for fixed $m_{\tilde{\chi}^0}$, the rate of annihilation increases with $m_A$ (since always $m_A < 2m_{\chi^0}$ and for increasing $m_A$ we approach closer the pole in the s-channel). Thus, for fixed $m_{\tilde{\chi}^0}$, $\Omega h^2$ increases when $m_A$ decreases. Its lower bound corresponds to the upper bound on $m_A$ for this value of $m_{\tilde{\chi}^0}$. The net effect is shown in Fig. 3a; the broadness of the band is determined by the discussed above dependence on $m_A$ for fixed $m_{\tilde{\chi}^0}$. Finally, we can now understand the dependence of $\Omega h^2$ on $m_A$ shown in Fig. 3b, whose relevant feature is the lower bound on $\Omega h^2$ which is increasing with $m_A$. For fixed $m_A$, the bound corresponds to the lower limit on $m_{\chi^0}$ (see Fig. 1a) which is increasing with increasing $m_A$. Thus, the rise of $\Omega h^2$ with $m_{\tilde{\chi}^0}$ translates itself into the rise of the lower bound on $\Omega h^2$ with $m_A$. Clearly, it remains to be checked if the lower bound on $m_{H^+} \approx m_A$ obtained from BR($b \to s\gamma$) is compatible with $\Omega h^2 < 1$. The result is shown in Fig. 4: the combination of the two constraints strongly disfavours the minimal SO(10) model with universal soft supersymmetry breaking terms at the GUT scale.

It is, therefore, very interesting to address the same question for the version of the model with non–universal soft supersymmetry breaking terms. In the minimal SO(10) model with $Y_t \approx Y_b \approx Y_\tau$ radiative electroweak breaking is very sensitive to departures from universality and qualitatively new solutions appear with non–universal Higgs and/or squark masses.

It is clear from our discussion of the universal case that the strong constraints from $b \to s\gamma$ and the neutralino relic abundance follow from the combination of the two properties: a) gaugino–like neutralinos b) negative corrections to $m_b$, which imply positive chargino
contribution to the amplitude for $b \to s\gamma$ (the sign of $\mu A_t$ is correlated with the sign of $\mu M_2$ by the RG running). A departure from universality of the soft terms can change both properties of the solutions. Two types of non–universalities have been classified according to whether (A) $\mu \gg M_{1/2}$ (still gaugino–like lightest neutralino) or (B) $\mu < M_{1/2}$ (large, or even dominant, higgsino component in the lightest neutralino). In both cases one can have solutions with small corrections $\delta m_b/m_b \leq 0.1$, say. Thus, Yukawa and gauge coupling unification is now consistent with both signs of the correction $\delta m_b$, while $m_b$ remains in the acceptable range. Nevertheless, with gaugino–like neutralinos (A) the constraints from $b \to s\gamma$ and $\Omega h^2 < 1$ remain critical. The main annihilation channel is the one with CP-odd Higgs exchange. Since for the same reasons as in the universal case $\Omega h^2$ is rising with $m_{\tilde{\chi}^0}$, and the annihilation amplitude is inversely proportional to $|m_A^2 - 4m_{\tilde{\chi}^0}^2|$ (typically, now, $m_A > 2m_{\tilde{\chi}^0}$, as eq. (3) is no longer valid in the non-universal case), the condition $\Omega h^2 < 1$ gives us an upper bound on $m_A$. The corresponding contribution to $b \to s\gamma$ from the charged Higgs boson exchange is generically in conflict with the experimental result. The smallness of the correction $\delta m_b/m_b$ allows now, in principle, for both signs of this correction and, in consequence, for both relative signs of the $H^+$ and $\tilde{\chi}^+$ contribution to $b \to s\gamma$. However, the latter turns out to be negligible and cannot cancel out too large corrections from the $H^+$-exchange: for this class of non-universal scalar masses (with $\mu \gg M_{1/2}$) the smallness of $\delta m_b/m_b$ can be achieved only at the expense of very heavy squarks, $m_{\tilde{q}} \sim \mathcal{O}(2 \text{ GeV})$ and the squark–chargino contribution to $b \to s\gamma$ is strongly suppressed.

The constraints discussed in this paper are easily satisfied for the class of non–universal scalar masses which leads to a higgsino–like lightest neutralino. First of all, the neutralino annihilation can proceed now by $Z$ exchange and essentially does not constrain the parameter space (apart from the known general limits on the neutralino mass). The relic abundance of the lightest neutralino is typically small, $\Omega h^2 \sim 10^{-2} - 10^{-1}$ but still remains cosmologically interesting. Moreover, the supersymmetric contribution to the $BR(b \to s\gamma)$ can be small due to the cancellation between the charged Higgs boson and higgsino amplitudes. In the limit of a pure higgsino–like lightest neutralino, $(m_{\tilde{\chi}^+} \approx \mu)$, this can be seen from formula (3) taken in the limit $x = m_{\tilde{q}}^2/m_{\tilde{\chi}^+}^2 \to \infty$. For the considered class of non–universal scalar masses the limit is a good approximation: radiative electroweak breaking gives solutions \( \tilde{f} \) with $\mu < M_{1/2}$ and the condition

$$0.1 > \left| \frac{\delta m_b}{m_b} \right| \sim \left| \frac{\mu M_{\tilde{g}}}{m_{\tilde{q}}^2} \right|,$$

(12)

with $M_{\tilde{g}} \sim 2.7 M_{1/2}$ and $m_{\tilde{q}}^2 \approx \mathcal{O}(5) M_{1/2}^2$, gives $\mu \leq \frac{1}{3} M_{1/2}$, i.e. $\mu \leq \frac{1}{6} m_{\tilde{q}}$. In the limit $x \to \infty$

$$\Delta f^{(3)} = f^{(3)}(x) - f^{(3)}(x + \delta) \approx -\frac{\delta \ln x}{x},$$

(13)

where

$$x = \frac{m_{\tilde{q}}^2}{\mu^2}, \quad \delta = \frac{\Delta m_{\tilde{q}}^2}{\mu^2} \approx \frac{2 A_t m_{\tilde{q}}}{\mu^2}.$$

(14)

Using the RG running we have $A_t \approx -\mathcal{O}(2 - 3) M_{1/2}$ and we indeed estimate that the contribution (8) and (9) can be of the same order of magnitude: For fixed $m_{\tilde{\chi}^+} \approx \mu$ the
chargino contribution increases when the squark mass (i.e. $M_{1/2}$) decreases. However, the requirement $\delta m_b/m_b < 0.1$ gives a lower bound on $M_{1/2}$, i.e. a lower bound on $m_{\tilde{q}}$, for fixed $\mu$ and, therefore, an upper bound for the chargino contribution. Since squarks are always much heavier than charginos, this upper bound remains strong (of the order of the $H^+$ contribution) even for light charginos. It decreases as $\mu$ is increasing because, for the maximal value of the ratio $\mu/M_{1/2}$ (fixed by $\delta m_b/m_b$), chargino contribution is proportional to $m_t/M_{1/2}$. We plot in Fig. 5 the value of the BR($b \to s\gamma$) versus $\Omega h^2$ for the solutions taken from ref.[6] for $m_t = 180$ GeV, $\tan \beta = 53$, $m^2_{H_1} = 2 m^2_0$, $m^2_{H_2} = 1.5 m^2_0$ and the GUT scale values of the other scalar masses being $m^2_0$. This choice of $m_t$ and $\tan \beta$ values is consistent with Yukawa and gauge coupling unification and the (pole) bottom quark mass in the experimental range, now with $|\delta m_b/m_b| < 0.1$ (for $\alpha_s = 0.119$). The points which satisfy both constraints correspond to $\mu M_{1/2} > 0$, i.e. give positive suSy correction to $m_b$.

In summary, the minimal SO(10) model with universal soft supersymmetry breaking terms at the GUT scale is strongly disfavoured by the combination of constraints from $b \to s\gamma$ and $\Omega h^2 < 1$ for the relic abundance of the lightest neutralino. Those constraints are however easily satisfied by the model with certain class of non-universal scalar masses which gives small supersymmetric corrections to the bottom quark mass and light higgsino-like neutralino.

Acknowledgements The work of F.M.B. was supported by the Bundesministerium für Forschung und Technologie, Bonn, Germany, under contracts 05 5 HH 91P(8) and 06 TM 732. She also acknowledges the partial support of the EEC Program Human Capital and Mobility through Network Physics High Energy Colliders CHRX-CT93-0357 (DG 12 COMA) and of the CEC science project SC1-CT91-0729. M. O. and S. P. acknowledge support from the Polish Committee of Scientific Research. F.M. B. and S. P. thank respectively the hospitality of the CERN Theory Division and of the Aspen Center for Physics where parts of this work were carried out.
References

[1] B. Anantharayan, G. Lazarides and Q. Shafi, *Phys. Rev.* **D44** (1991) 1613
S. Dimopoulos, L.J. Hall and S. Raby, *Phys. Rev. Lett.* **68** (1992) 1984 and *Phys. Rev.* **D45** (1992) 4192
G.W. Anderson, S. Raby, S. Dimopoulos and L.J. Hall, *Phys. Rev. D47* (1993) 3702
G.W. Anderson, S. Raby, S. Dimopoulos, L.J. Hall and G.D. Starkman, *Phys. Rev. D49* (1994) 3660.

[2] M. Carena, M. Olechowski, S. Pokorski and C. Wagner, *Nucl. Phys.* **B426** (1994) 269.

[3] L.J. Hall, R. Rattazzi and H. Sarid, preprint LBL–33997 (1993),
R. Hampfling, *Phys. Rev.* **D49** (1994) 6168.

[4] T. Banks, *Nucl. Phys.* **B303** (1988) 172,
M. Olechowski and S. Pokorski, *Phys. Lett.* **B214** (1988) 393,
S. Pokorski, “How is the isotopic symmetry of quark masses broken?”, in Proc. XIIth Int. Workshop on Weak Interactions and Neutrinos, Ginosar, Israel, *Nucl. Phys. B13* (Proc. Supp.) (1990) 606.

[5] M. Olechowski and S. Pokorski, *Phys. Lett.* **B214** (1988) 393;
G.F. Giudice and G. Ridolfi, *Z. Phys.* **C41** (1988) 447;
H.P. Nilles, “Beyond the Standard Model”, in Proceedings of the 1990 Theoretical Advanced Study Institute in Elementary Particle Physics, p. 633; Eds. M. Cvetic and P. Langacker, World Scientific;
P.H. Chankowski, Diploma Thesis (1990), University of Warsaw;
A. Seidl, Diploma Thesis (1990), Technical University, Munich;
W. Majerotto and B. Mösslacher, *Z. Phys.* **C48** (1990) 273;
S. Bertolini, F. Borzumati, A. Masiero and G. Ridolfi, *Nucl. Phys.* **B353** (1991) 591;
M. Drees and M.M. Nojiri, *Nucl. Phys.* **B369** (1992) 54;
B. Ananthanarayan, G. Lazarides and Q. Shafi, Bartol Research Institute preprint BA–92–29.

[6] D. Matalliotakis and H.P. Nilles, Munich preprint MPI–PhT/94-39, TUM-HEP-201-94 (1994)
N. Polonsky and A. Pomarol, University of Pennsylvania preprint UPR–0627T (1994)
N. Polonsky and A. Pomarol, University of Pennsylvania preprint UPR–0616–T (1994)
R. Hempfling, DESY preprint 94-078 (1994);
A. Leyda and C. Munoz, *Phys. Lett.* **B317** (1993) 82
T. Kobayashi, D. Suematsu and Y. Yamagishi, Kanazawa report KANAZAWA–94–06, [hep–ph 9403330](https://arxiv.org/abs/hep–ph 9403330);
R. Rattazzi, U. Sardir and L.J. Hall, talk presented at the second IFT Workshop on Yukawa couplings and the origin of mass, February 1994 Gainesville, Florida, SU–ITP–94/15, [hep–ph 9405313](https://arxiv.org/abs/hep–ph 9405313).
Y. Kawamura, H. Murayama and M. Yamaguchi, DPSU–9402 and LBL–35731, hep–ph 9406245
M. Carena and C. Wagner, preprint CERN–TH.7321/94 (1994).

[7] M. Olechowski and S. Pokorski, preprint MPI–Ph/94–40 (1994) to be published in Phys. Lett. B.

[8] M. Olechowski and S. Pokorski, Nucl. Phys. B404 (1993) 590.

[9] R. Ammar et. al (CLEO Collaboration), CLEO CONF 94-1.

[10] F.M. Borzumati, M. Drees, M.M. Nojiri, Phys. Rev. D51 (1994) 27.

[11] J.F. Gunion and H.E. Haber, Nucl. Phys. B272 (1986) 1.

[12] S. Bertolini, F. Borzumati, A. Masiero and G. Ridolfi, Nucl. Phys. B353 (1991) 591,
R. Barbieri and G.F. Giudice, Phys. Lett. B309 (1993) 86.

[13] G. Gelmini and P. Gondolo, Nucl. Phys. B360 (1991) 145,
P. Gondolo, M. Olechowski and S. Pokorski, to appear.

[14] A. J. Buras, M. Misiak, M. Münz and S. Pokorski, Nucl. Phys. B424 (1994) 374.
FIGURE CAPTIONS

Fig. 1. a) The spectrum of the CP odd Higgs boson mass $m_A$ plotted versus the lighter chargino mass $m_{\tilde{\chi}^\pm_2}$ in the minimal SO(10) model with radiative electroweak breaking and universal soft scalar masses at the GUT scale. The values of the parameters are: $m_t = 160$ GeV, $\tan \beta = 40$, $\alpha_s = 0.129$ and the low energy values of the soft squark masses $m_Q$ and $m_U$ were scanned up to 2 TeV. All existing experimental constraints on the supersymmetric particles are taken into account.

b) Same as a) for the higgsino component $Z_{13}$ of the lightest neutralino plotted versus the neutralino mass $m_{\tilde{\chi}^0_1}$.

Fig. 2. Same as Fig. 1a for $BR(b \to s\gamma)$ plotted versus $m_{H^+}$. The horizontal lines are experimental $2\sigma$ bounds. The uncertainties discussed in ref. [14] are included in the theoretical bound.

Fig. 3. a) Same as Fig. 1a for $\Omega h^2$ plotted versus $m_{\tilde{\chi}^0_1}$.

b) Same as Fig. 1a for $\Omega h^2$ plotted versus $m_A$.

Fig. 4. Same as Fig. 1a for $BR(b \to s\gamma)$ plotted versus $\Omega h^2$. The region consistent with $\Omega h^2 < 1$ and experimental $2\sigma$ bound for $BR(b \to s\gamma)$ is marked by the dashed line.

Fig. 5. $BR(b \to s\gamma)$ plotted versus $\Omega h^2$ in the minimal $SO(10)$ model with radiative electroweak breaking and non-universal soft scalar masses at the GUT scale for $m_t = 180$ GeV, $\tan \beta = 53$, $m_{H_1}^2 = 2m_0^2$, $m_{H_1}^2 = 1.5m_0^2$ and the GUT scale values of the other scalar masses $m_0^2$; the low energy values of the $m_Q$ and $m_U$ were scanned up to 2 TeV.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9412379v2
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9412379v2
This figure "fig1-4.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9412379v2