SUPERSYMMETRY AT THE ELECTROWEAK SCALE*

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Dedicated to Andrzej Białas in honour of his 60th birthday

We discuss how realistic is the possibility of the existence of supersymmetric particles with masses of order $\mathcal{O}(M_Z)$.

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1. Introduction

Physics beyond the Standard Model (SM) is a challenging issue. Although there is for it as yet no compelling experimental evidence, very few (if anybody) view the SM as the final theory of fundamental interactions. If we accept this point of view, that the SM is only an effective "low energy" description with its roots in a deeper high energy theory, we immediately face the so-called hierarchy problem: what determines and stabilizes the electroweak scale versus the scale of new physics? The larger the latter the more serious the hierarchy problem. The most natural expectation is to have the scale of new physics close to the electroweak scale.

Supersymmetry offers a solution to the hierarchy problem: the new scale is the scale of soft supersymmetry breaking. Superpartner masses are expected to be at most within $\mathcal{O}(1\ \text{TeV})$ range and preferably even closer to M_Z. In this paper we address the question of how realistic is this expectation.

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In the last few years we witness an important progress both on the experimental and theoretical side which a) very strongly constrains potential presence of supersymmetry at $\mathcal{O}(M_Z)$ (in fact any extension of the SM is strongly constrained); b) gives some indirect hints that (perhaps) it indeed manifests itself already at that scale.

It is very interesting that within the Minimal Supersymmetric Standard Model (MSSM) the hints for new physics can be accommodated in consistency with the overall very good agreement between experiment and the SM. Moreover, this consistency exists only for a well defined (and narrow) range of supersymmetric parameters – good news for experimental search for supersymmetry.

The main points of the experimental progress are the following:

- Precision electroweak data (LEP, SLAC);
- Measurement of the top quark mass, $m_t = (175 \pm 9)$ GeV (Fermilab); the top quark mass is a very important parameter in the calculations of the electrowek observables and rare processes;
- High precision in measurements of rare processes, in particular $\overline{K}^0 - K^0$ (CP violating parameter ε), $\overline{B}^0 - B^0$ and $b \to s\gamma$

As we shall discuss in more detail in the following, all those results are in an overall very good agreement with the SM and constrain very strongly any of its extensions, in particular the supersymmetric extension.

Moreover, from direct searches for supersymmetric particles we have several important lower limits on their masses. The recent run of LEP1.3 gives a bound on the chargino mass $m_C > 65$ GeV, provided $|m_C - m_N| \gtrsim 5$ GeV (m_N is the neutralino mass) and under the assumption of $R-$parity conservation [1]. There are also several other, more model dependent, limits on the neutralino, stop, gluino and squark masses [2, 3, 1]

In addition to the mentioned above results, there exist also several experimental "puzzles". The main one is the large value of $R_b \equiv \Gamma(Z^0 \to \bar{b}b)/\Gamma(Z^0 \to \text{hadr}) = 0.2211 \pm 0.0016$ [4] which has provoked speculations on being a sign of new physics. The ALEPH 4–jets events [5] and the Tevatron event [6] complete this list of surprising findings, statistically too insignificant to be fully convincing but challenging enough to stimulate speculations about new physics.

On the theoretical side, the progress of recent years amounts to a development of quantitative low energy supersymmetric phenomenology, with the same precision calculations as in the SM. The experimental data can be confronted with the model in a fully quantitative way.

2. Constraints on new physics from precision electroweak data; the R_b anomaly

2.1. The Standard Model description

The success of the SM is best measured by its description of the bulk of the electroweak data. In the following Table we present the latest data (Moriond'96) [4] together with the results of the best fit in the SM. The fitted parameters are m_t, M_H and $\alpha_s(M_Z)$.

We see an overall excellent agreement of the SM with the data. The only clear discrepancy is the value of R_b. The experimental value of R_c is also 1.6σ away from the prediction but this is statistically much less significant. Finally, there are two $\sim 2\sigma$ deviations in the leptonic left-right asymmetry and the parameter $\mathcal{A}_b$. Both measurement come from SLAC and those deviations look like merely experimental problems of some mismatch between the SLAC and LEP data. Indeed, A^l_{LR} is a measure of the $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ and it disagrees with the LEP measurement which can be extracted from the parameters $\mathcal{A}_e$, $\mathcal{A}_\tau$, A^l_{FB}. The direct SLAC measurement of $\mathcal{A}_b$ disagrees with the indirect LEP determination from A^b_{FB}.

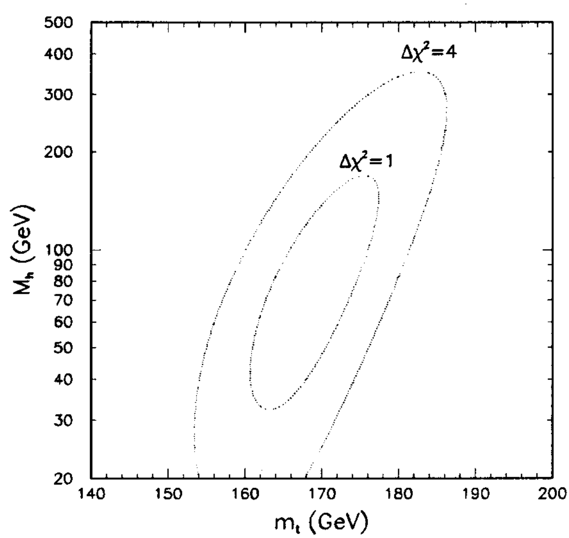

Fig. 1. $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 4$ contours in the plane (m_t, M_h) for the fit in the SM.

The precision of the data is already high enough to be sensitive to the Higgs boson mass (which enters into the calculations only logarithmically). The full fit gives $M_h = 76^{+93}_{-44}(1\sigma)^{+277}_{-76}(2\sigma)$. whereas in the fit without R_b

and R_c we get $M_h = 94^{+117}_{-55}(1\sigma)^{+346}_{-94}(2\sigma)$. The $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 4$ contours in the (m_t, M_h) plane are shown in Fig. 1. We observe that the fitted value of M_h does not depend much on whether R_b is included or not into the fit. This is important in view of the large deviation in R_b. However, some caution in the conclusions is still necessary: if both R_b and A^l_{LR} are absent from the fitted observables we get $M_h = 205^{+226}_{-116}(1\sigma)^{+660}_{-170}(2\sigma)$. Thus, the data are consistent with a light Higgs boson but the 2σ upper bound depends strongly on the inclusion of the SLD result for A^l_{LR} in the fit.

One remark is in order here. The SLD value of A^l_{LR} gives $\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23049 \pm 0.00050$ whereas the LEP value is $\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23178 \pm 0.00031$. In the SM, the value of $\sin^2\theta^{\text{lept}}_{\text{eff}}$ can be very precisely calculated (instead of being determined from a global fit like in Table I) in terms of M_Z, m_t and M_h. We get *e.g.*the results shown in Table II.

TABLE I

Comparison of the experimental data [4] for various electroweak observables with the predictions of the best fit in the SM. Two columns show predictions with and without R_b, R_c included in the fit.

X	X_{exp}	ΔX_{exp}	with R_b, R_c	pull	no R_b, R_c	pull
M_Z	91.1884	0.0022	input	0	input	0
Γ_Z	2.4964	0.0032	2.4975	−0.33	2.4978	−0.44
σ_{hadr}	41.49	0.078	41.448	0.54	41.452	0.49
$\mathcal{A}_e(P_\tau)$	0.1394	0.0069	0.1472	−1.13	0.1475	−1.17
$\mathcal{A}_\tau(P_\tau)$	0.1429	0.0079	0.1472	−0.54	0.1475	−0.58
A^l_{FB}	0.0171	0.0011	0.0162	0.78	0.0163	0.72
R_l	20.788	0.032	20.780	0.26	20.775	0.40
$\sin^2\theta(Q_{FB})$	0.2320	0.0010	0.23150	0.50	0.23146	0.54
A^l_{LR}	0.1551	0.0040	0.1472	1.98	0.1475	1.91
R_b	0.2211	0.0016	0.21619	3.07	0.21608	3.14
R_c	0.1598	0.0069	0.1710	−1.62	0.1710	−1.63
A^b_{FB}	0.1002	0.0028	0.1032	−1.07	0.1034	−1.14
A^c_{FB}	0.0759	0.0051	0.0737	0.43	0.0739	0.39
$\mathcal{A}_b$	0.842	0.052	0.935	−1.79	0.935	−1.78
$\mathcal{A}_c$	0.618	0.091	0.668	−0.55	0.668	−0.55
M_W	80.33	0.15	80.361	−0.20	80.372	−0.28
$1 - M^2_W/M^2_Z$	0.2257	0.0047	0.22338	0.49	0.22317	0.54
m_t	175	9	169	0.44	172	0.11

TABLE II

Predictions in the SM for $\sin^2\theta^{\rm eff}_{\rm lept}$ for various top quark and Higgs boson masses. The error of this predictions (coming mainly from the uncertainty of the hadronic contribution to the photon vacuum polarization) is ± 0.00025.

m_t	170	180	190	170	180	190
M_h	60	60	60	150	150	150
$\sin^2\theta^{\rm eff}_{\rm lept}$	0.23135	0.23101	0.23066	0.23182	0.23149	0.23114

It is clear that the SLD measurement favours large values of m_t and small values of M_h which give worse fit to the other observables.

Another point of recent interest is the value of $\alpha_s(M_Z)$ obtained from the electroweak fits[1]. We get $\alpha_s(M_Z) = 0.122 \pm 0.005$ and this value is somewhat larger then the value obtained from the deep inelastic scattering data [7] $\alpha_s(M_Z) = 0.112 \pm 0.005$.

2.2. Supersymmetric corrections to the electroweak observables

We can interpret the SM fits as the MSSM fits with all superpartners heavy enough to be decoupled. Supersymmetry then just provides a rationale for a light Higgs boson: $M_h \sim \mathcal{O}(100 \text{ GeV})$ [2]. Since the best fit in the SM is consistent with the Higgs boson mass precisely in this range we can expect that the MSSM with heavy enough superpartners gives as good a fit to the precision electroweak data as the SM. Of course, such a fit faces the same problem of the R_b anomaly.

It is then an interesting question if supersymmetry can help to resolve the R_b anomaly. The issue has been addressed in a number of papers [10–17]. It is well known already for some time that in the MSSM there are new contributions to the $Z^0\bar{b}b$ vertex which can significantly enhance the value of R_b (but do not change R_c) if some superpartners are sufficiently light [18, 10, 12–16]. More specifically, for low (large) $\tan\beta$ the dominant contributions are chargino–stop (CP–odd Higgs boson and chargino–stop) loops. Moreover it is also known that new physics in $\Gamma_{Z^0\to\bar{b}b}$ and therefore additional contribution to the total hadronic width of the Z^0 boson would lower the fitted value of $\alpha_s(M_Z)$ [19, 11, 20], in better agreement with its determination from low energy data [7].

[1] In the electroweak fits the value of $\alpha_s(M_Z)$ is very precisely determined by strong corrections to the total hadronic Z^0 width. This quantity is calculated with high precision (up to $\mathcal{O}(\alpha_s^3)$) and the experimental error is also very small: $\Gamma_h = 1745.0 \pm 3.0$.

[2] The important one loop corrections to Higgs boson masses in the MSSM have been calculated in Refs [8]. Less important two loop corrections are also known [9].

Any improvement in R_b must not destroy the perfect agreement of the SM with the other precision LEP measurements and must be consistent with several other experimental constraints (which will be listed later on). It is, therefore, important to discuss the changes in R_b in the context of global fits to the electroweak data (and with all additional constraints included). We begin therefore with a brief overview of the SUSY corrections to the electroweak observables.

The bulk of the precision data, such as M_W, Γ_Z, $\sin^2\theta^{\rm eff}_{\rm lept}$ (*i.e.* all listed in Table I asymmetries), ..., are mostly sensitive to the $\Delta\rho$ parameter which measures the violation of the custodial $SU_V(2)$ symmetry. The contribution of the top–bottom quark mass spliting to $\Delta\rho$ leaves very little room for new contributions: $\Delta\rho < 0.0015$ at 95% C.L. [21]. Therefore, in order to maintain the overall good agreement of the fit with the data we must avoid new sources of the custodial $SU_V(2)$ symmetry breaking in the left currents. In the MSSM, such $SU_V(2)$ violation may originate in the left-handed squark and slepton mass matrix elements (which we denote with capital letters *e.g.* $M^2_{\tilde{t}_L} = m^2_{\tilde{q}_L} + m^2_t + t_\beta(M^2_Z - 4M^2_W)$ and similarly for the other squarks and sleptons):

$$\begin{aligned} M^2_{\tilde{l}_L} - M^2_{\tilde{\nu}} &= t_\beta M^2_W\,, \\ M^2_{\tilde{t}_L} - M^2_{\tilde{b}_L} &= m^2_t - m^2_b - t_\beta M^2_W\,, \end{aligned} \tag{1}$$

where $t_\beta \equiv (\tan^2\beta - 1)/(\tan^2\beta + 1)$ ($\tan\beta$ is the ratio v_2/v_1 of the VEVS of the two Higgs doublets of the MSSM). They contribute to $\Delta\rho$ always with the same sign as the $t-b$ mass splitting. It should be stressed that the supersymmetric contribution to $\Delta\rho$ is merely sensitive to $m_{\tilde{l}_L}$ and $m_{\tilde{q}_L}$ which determine the magnitude of the splitting in Eq. (1) relative to the masses $M_{\tilde{t}_L}$ *etc.* The dependence on the right handed sfermion masses enters only through the left right mixing. This also means that the contribution to $\Delta\rho$ is almost insensitive to the masses of squarks of the first two generations: in their left handed components there is no source of large $SU_V(2)$ violation (however, slepton contribution to $\Delta\rho$ is generation independent). Also, the $\Delta\rho$ is rather weakly dependent on the chargino and neutralino masses $m_{C^\pm}$, m_{N^0} and on the Higgs sector parameters [3]. Finally, it is worth noting different behaviour of the slepton and squark contributions to $\Delta\rho$ with $\tan\beta$: the former vanishes in the limit $\tan\beta \to 1$ whereas the latter is maximal in this limit and only slightly decreases as $\tan\beta \to \infty$.

Thus, in order to maintain the good agreement of the SM with the data, the left squarks of the third generation and all left sleptons must be

[3] This is due to generically weak $SU_V(2)$ breaking effects in these sectors.

sufficiently heavy [22, 13], say, > $\mathcal{O}$(300GeV). At the same time, an increase in R_b is sensitive mainly to the masses and couplings of the right handed top squark, charginos and — in the case of large $\tan\beta$ — of the right handed sbottom and CP–odd Higgs boson A^0 [18], which do not affect $\Delta\rho$ too much. Therefore, the requirement of a good overall fit is not in conflict with requirement of an enhancement of R_b [13] and they imply a hierarchy:

$$M_{\tilde{t}_L} \gg M_{\tilde{t}_R} \quad \text{or} \quad M_{\tilde{t}_2} \gg M_{\tilde{t}_1} \tag{2}$$

with small left-right mixing.

2.3. R_b in the MSSM

We shall now discuss in more detail the supersymmetric contribution to R_b in the low $\tan\beta$ region. The chargino — stop loops can be realized in two ways: with stop coupled to Z^0 and with charginos coupled to Z^0. In both cases the lighter the stop and chargino the larger is the positive contribution. We recall the pattern of the chargino sector (masses and mixings). The chargino mass matrix

$$\mathcal{L}_{\mathbf{mass}} = -\tfrac{1}{2}(\chi^+, \chi^-) \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \begin{pmatrix} \chi^+ \\ \chi^- \end{pmatrix} + \text{h.c.} \tag{3}$$

with

$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix} \tag{4}$$

is diagonalized by two unitary matrices Z_+ and Z_-:

$$Z_-^T X Z_+ = \quad \text{diag}(m_{C_1}, m_{C_2})$$

with $0 < m_{C_1} < m_{C_2}$ (we follow the convention and notation of Ref. [23]) which determine the projection of the physical two-component states $\lambda_i^\pm$ ($i = 1, 2$) on the gaugino and higgsino two-component weak eigenstates $(-i\psi^+, h_2^+, -i\psi^-, h_1^-) \equiv (\chi^+, \chi^-)$

$$h_2^+ = Z_+^{2i}\lambda_i^+ , \quad h_1^- = Z_-^{2i}\lambda_i^- , \tag{5}$$

$$\psi^\pm = iZ_\pm^{1i}\lambda_i^\pm \tag{6}$$

with the Dirac charginos defined as

$$C_i^- = \begin{pmatrix} \lambda_i^- \\ \overline{\lambda_i^+} \end{pmatrix} . \tag{7}$$

Moreover, the $b\tilde{t}_1C^-$ coupling is enhanced for a right handed stop (it is then proportional to the top quark Yukawa coupling). Then, however, the stop coupling to Z^0 is suppressed (it is proportional to $g\sin^2\theta_W$) and significant contribution can only come from the diagrams in which charginos are coupled to Z^0. Their actual magnitude depend on the interplay of the couplings in the $C_i^-\tilde{t}_1b$ vertex and the $Z^0C_i^-C_j^-$ vertex. The first one is large only for charginos with large up-higgsino component, the second — for charginos with large gaugino component in at least one of its two-component spinors. It has been observed that this combination never happens for $\mu > 0$. Large R_b can then only be achieved at the expense of extremly light C_j^- and $\tilde{t}_1$. In addition, for fixed m_{C_1} and $M_{\tilde{t}_1}$, R_b is larger for $r > 1$ *i.e.* for higgsino-like chargino as the enhancement of the $C_1^-\tilde{t}_1b$ coupling is more important than of the $Z^0C_1^-C_1^-$ coupling.

For $\mu < 0$ the situation is much more favourable. In the range $r \approx 1 \pm 0.5$ a light chargino can be a strongly mixed state with a large up-higgsino and gaugino components (the higgsino-gaugino mixing comes from the chargino mass matrix). Large couplings in both vertices of the diagram with charginos coupled to Z^0 give significant increase in R_b even for the lighter chargino as heavy as $80 - 90$ GeV (similar increase in R_b for $\mu > 0$ requires $m_{C_1} \approx 50$ GeV and $M_{\tilde{t}_1} \approx 50$ GeV).

A sample of results for R_b as a function of the chargino mass, for several values of $M_2/|\mu|$ and two values of the lighter stop mass $M_{\tilde{t}_1} = 50$ and 60 GeV are shown in Fig. 2. (the left-right mixing angle of stops is fixed to $-6^o(+6^o)$ for $\mu < 0 (> 0)$ so that the constraint coming from $BR(b \to s\gamma)$ is satisfied; see the discussion in the next section). For $\mu < 0$ the curves terminate (for light charginos) at the kinematical limits which depend on $\tan\beta$ and $M_2/|\mu|$.

Significant enhancement of R_b is also possible for large $\tan\beta$ values, $\tan\beta \approx m_t/m_b$ [18]. In this case, in addition to the stop–chargino contribution there can be even larger positive contribution from the h^0, H^0 and A^0 exchanges in the loops, provided those particles are sufficiently light (in this range of $\tan\beta$, $M_h \approx M_A$) and non-negligible sbottom–neutralino loop contributions. The dependence of R_b on the chargino mass for $m_t = 170$, $\tan\beta = 50$, $M_A = 55$ GeV and $M_{\tilde{b}_1} = 130$ GeV is shown in Fig. 3. The main difference with the low $\tan\beta$ case is the independence of the results on the sign of μ (which can be traced back to the approximate symmetry of the chargino masses and mixings under $\mu \to -\mu$). Due to the combined effect of A^0 and chargino-stop and neutralino-sbottom exchanges, R_b remains as large as 0.2178 even when all three masses M_{A^0}, m_{C_1} and $M_{\tilde{t}_1}$ are taken to be 65 GeV.

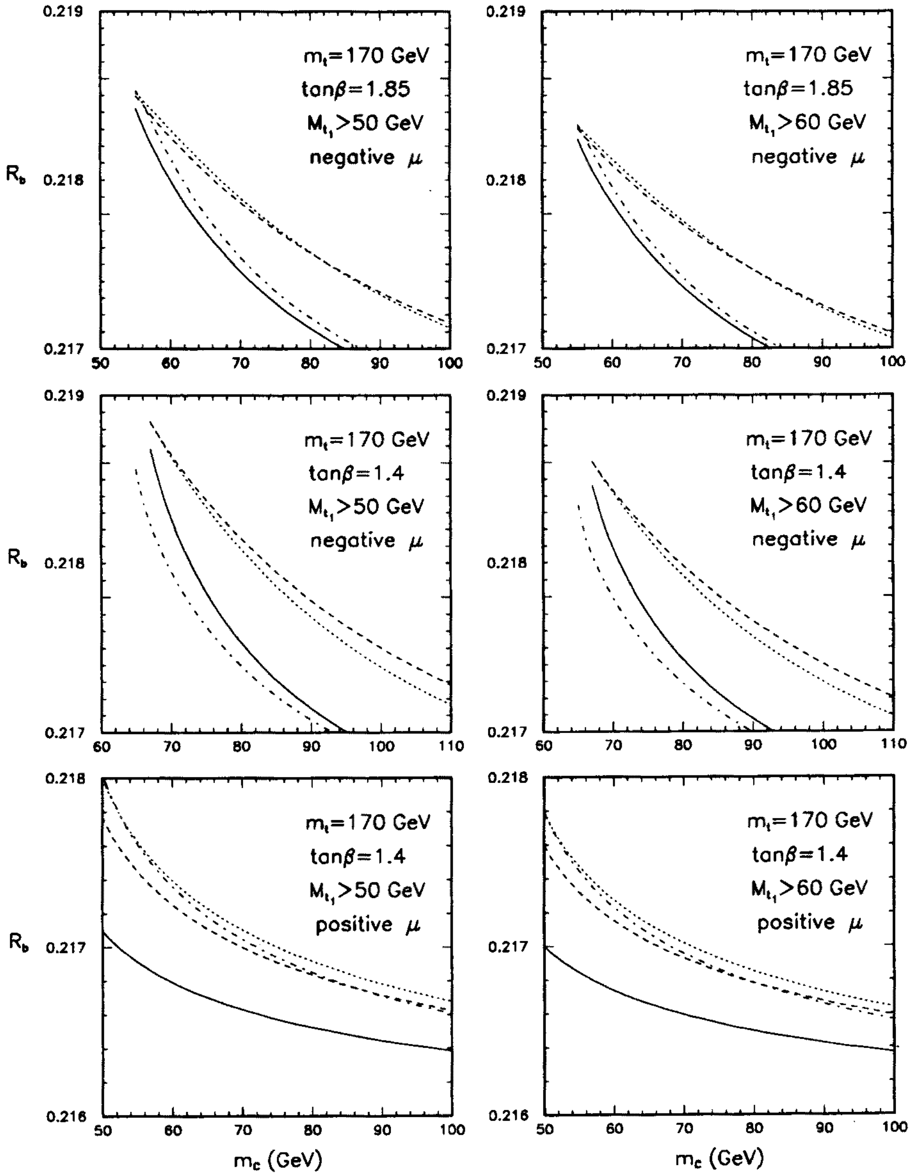

Fig. 2. R_b as a function of m_{C^-} for $r \equiv M_2/|\mu| = 0.5$ (solid lines), 1 (dashed), 1.5 (dotted), and 3 (dash-dotted) for both signs of μ for $m_t = 170$ GeV, $\tan\beta = 1.4$ and 1.85, $M_A = M_{\tilde{t}_2} = 1$ TeV for $M_{\tilde{t}_1} > 50$ GeV (left pannels) and $M_{\tilde{t}_1} > 60$ GeV (right pannels). $\theta_t = -6^o$ for $\mu < 0$ and $\theta_t = +7^o$ for $\mu > 0$.

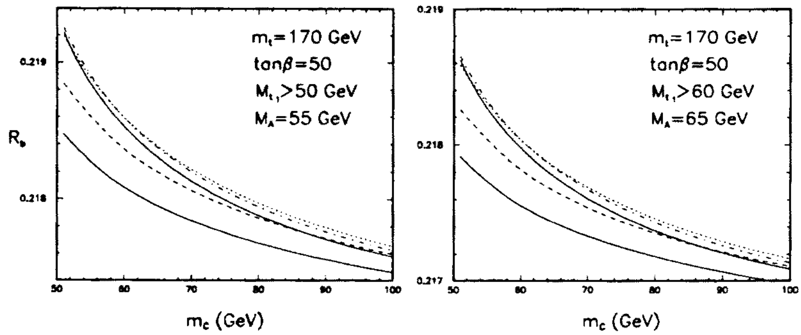

Fig. 3. R_b as a function of m_{C^-} for $r \equiv M_2/|\mu| = 1$ (lower solid lines), 1.5 (dashed), 3 (dotted), 5 (dash-dotted) and 10 (upper solid) for $m_t = 170$ GeV, $\tan\beta = 50$ $M_{\tilde{t}_2} = 1$ TeV for $M_A = 55$ GeV $M_{\tilde{t}_1} > 50$ GeV (left pannel) and $M_A = 65$ GeV $M_{\tilde{t}_1} > 60$ GeV (right pannel).

The results support our qualitative discussion. However, as stressed earlier they must be subject to constraints from the quality of the global fit to the electroweak data and from all other available experimental information. Those constraints often differ in the degree of their model dependence and are worth careful discussion. A good quality of a global fit to the data is mainly assured by heavy enough left-handed sfermions with no direct impact on the value of R_b. The main remaining effect is the contribution of the decay $Z^0 \to N_i^0 N_j^0$ to the total width Γ_Z. Their rôle depends on the assumption about the gaugino masses: with the GUT assumption, $M_1 \approx 0.5M_2$, the neutralino mass matrix is determined by the chargino one and for $m_{C^-} < 50 - 55$ GeV for $\mu > 0$ or $m_{C^-} < 55 - 70$ GeV for $\mu < 0$ the decay $Z^0 \to N_1^0 N_1^0$ generically contributes too much to Γ_Z and spoils the quality of the global fit. Clearly, this is avoided for $M_1 > 0.5M_2$.

We now turn to constraints which are not included in the global fit. There are several model independent limits which are relevant for R_b. However the impact of some of them on R_b is model dependent.

Model independent limit	Constrains R_b under the assumption:
$m_{C^-} > 47$ GeV	$--$
$M_{\tilde{t}_1} > 46$ GeV	$--$
$M_h > 60$ GeV	$--$
$BR(t \to \tilde{t}_1 N_i^0)$	M_1 versus M_2
$M_A > 55$ GeV	for large $\tan\beta$

The first two bounds limit the increase in R_b in an obvious way. The rôle of the lower limit on the Higgs boson mass (for a compact formula for radiatively corrected lighter Higgs boson mass in the limit $M_A \gg M_Z$ see [24]) depends on the mass of the heavier stop and the left-right mixing angle.

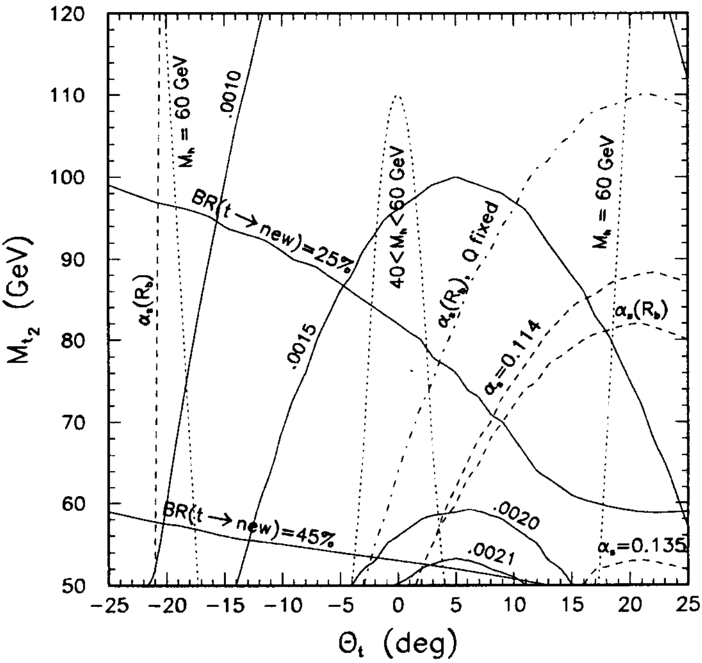

Fig. 4. Contours of constant $\delta R_b^{\rm SUSY}$ (solid lines) and various constraints in the plane $(\theta_t, M_{\tilde{t}_2})$ for $m_t = 170$ GeV, $\tan\beta = 1.4$, $M_2 = -\mu = 58$ GeV ($m_{C_1} = 85$ GeV), $M_A = M_{\tilde{t}_2} = 1$ TeV. Dashed and dash-doted lines show the $b \to s\gamma$ constraint with different treatement of α_s: $\alpha_s(R_b)$ denotes the curves obtained with $\alpha_s(M_Z) = 0.123 - 4\delta R_b^{\rm SUSY}$ and with the renormalization scale Q varied in the range $(m_b/2, 2m_b)$. The curve with Q fixed correspond to $Q = m_b = 4.7$ GeV and $\alpha_s(M_Z) = 0.123$ (for more details see the text). Dotted lines illustrate the Higgs boson mass constraint. The allowed region is bounded from below by the $BR(t \to \text{new}) = 45$ % curve and the parabolic $b \to s\gamma$ curve $\alpha_s(R_b)$ and from the left- and right- hand sides by the dotted curves $M_h = 60$ GeV. The area below the central dotted curve is also excluded.

For $M_{\tilde{t}_2} > 500$ GeV (as required for good quality of the global fit) and small mixing angles (necessary for large R_b) M_h is above the experimental limit[4] in a large range of the parameter space. Very small and large left-right mixing angles are, however, ruled out by this constraint. This is clearly seen in Fig. 4 where we show the allowed region in the $(M_{\tilde{t}_1}, \theta_t)$ plane for fixed M_2, μ $M_{\tilde{t}_2}$ and $\tan\beta$. The rôle of the top decay bound again

[4] Important rôle of the experimental lower bound on M_h in Ref. [16] in constraining the potential increase of R_b is due to the chosen upper bound $M_{\tilde{t}_2} < 250$ GeV which, anyway, looks too low from the point of view of a global fit.

depends (as for Γ_Z) on the model assumptions about M_1 versus M_2 values and on the ratio M_2/μ. For the curves shown in Fig. 3, the GUT relation $M_1 \approx 0.5M_2$ have been assumed. The list of model dependent constraints is also very interesting. We collect them in the following Table, together with the necessary model assumptions.

Model dependent limits	Assumptions
$m_{C^-} > 65$ GeV	$R-$parity conservation
for $\|m_{C^-} - m_{N^0}\| > 5$ GeV	(stable LSP)
$\Gamma(Z^0 \to N_1^0 N_1^0) < 4$ MeV	– –" – –
$BR(Z^0 \to N_1^0 N_2^0) < 10^{-4}$	– –" – –
D0 exclusion plot in $(M_{\tilde{t}_1}, m_{N_1^0})$	– –" – –
for $m_{C_1^-} > M_{\tilde{t}_1}$	
$(\tan\beta)_{\rm min} < \tan\beta < (\tan\beta)_{\rm max}$	perturbativity to the GUT scale
$M_2 > 36$ GeV	$M_3 \approx 3M_2$ and gluino search

Not only those limits depend on the assumed $R-$parity conservation but, in addition, their significance crucially depends on the ratio M_1/M_2. In general, the limits disappear or are unconstraining in the limiting case of chargino and neutralino closely degenerate in mass.

The results shown in Fig. 2 illustrate increase in R_b which is possible with only model independent constraints. They can be compared with the increase in R_b which is reachable in the most conservative case, in the MSSM with $R-$parity conservation and $M_1 \approx 0.5M_2$ (*i.e.* with all the constraints included and due attention to the quality of the global fit). A sample of such results is shown in Fig. 5. We see that even in this most conservative case $R_b = 0.2180 - 0.2185$ is realistic. In particular, in the low $\tan\beta$ region a chargino with mass $70 - 90$ GeV and with $\mu < 0$ remains an interesting possibility. The right handed stop can still be around 50 GeV but even with $M_{\tilde{t}} \sim 60 - 70$ GeV the effect on R_b is not negligible.

By relaxing the assumption about $R-$parity conservation and/or the GUT assumption for the gaugino masses the enhancement in R_b can be somewhat stronger and in even larger region of the parameter space. Both signs of μ are acceptable and chargino and stop as light as 50 GeV are acceptable. Very similar conclusions hold for the large $\tan\beta$ region, with the present experimental limit $M_A > 55$ GeV [2].

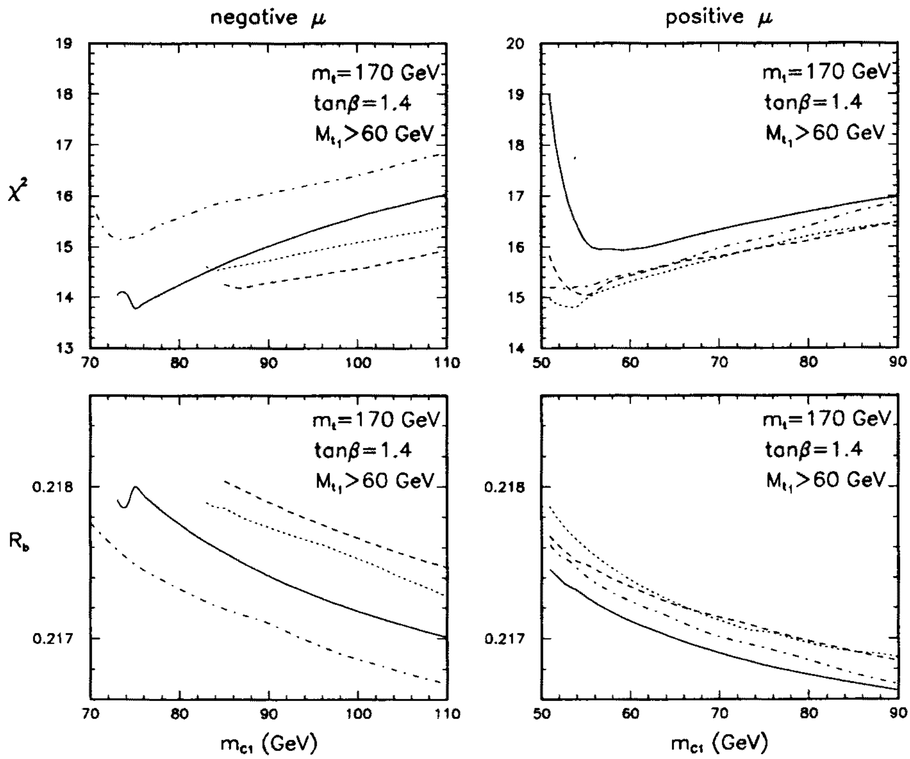

Fig. 5. χ^2 as a function of m_{C_1} for $r \equiv M_2/|\mu| = 0.5$ (solid lines), 1 (dashed), 1.5 (dotted) and 3 (dash-dotted) for both signs of μ for $m_t = 170$ GeV, $\tan\beta = 1.4$, $M_A = M_{\tilde{t}_2} = 1$ TeV. In lower pannels the best values of R_b with the restriction $\chi^2 < \chi^2_{\rm min} + 1$ (here $\chi^2_{\rm min}$ denotes the best χ^2 for fixed value of m_{C_1}) are shown. In addition we required $M_{\tilde{t}_1} > 60$ GeV. For $\mu < 0$ lighter chargino masses are excluded by the constraint $BR(Z^0 \to N_1 N_2) < 10^{-4}$.

2.4. Rare processes and light supersymmetric particles

There are several well known supersymmetric contributions to rare processes. In particular, supersymmetry may provide new sources of flavour violation in the soft terms. However, even assuming the absence of such new effects, there are obvious new contributions where $W^\pm - q$ SM loops are replaced by the $H^\pm - q$ loops and by $\tilde{W}^\pm(\tilde{H}^\pm) - \tilde{q}$ loops. Those can be expected to be very important in the presence of light chargino and stop and they contribute to all best measured observables: $\varepsilon-$ parameter for the $\overline{K}^0 - K^0$ system, Δm_B from $\overline{B}^0 - B^0$ mixing and $BR(b \to s\gamma)$.

There are two important facts to be remembered about these contributions. They are present even if quark and squark mass matrices are diagonal in the same super-Kobayashi-Maskawa basis. Then, the couplings in the $d_i\tilde{u}_jC^-$ vertex are given by the K-M mixing angles. They can depart from the K-M parametrization if squark mass matrices have flavour-off diagonal entries in the super-Kobayashi-Maskawa basis. Some of those entries are still totally unconstrained and this is precisely the case for the (right) up squark mass matrix which is relevant e.g. for the couplings $b\tilde{t}_RC^-$. Still, sizeable suppression compared to the K-M parametrization requires large flavour-off diagonal mass terms, of the order of diagonal ones. To remain on the conservative side we include the constraints from rare processes under the assumption of the K-M parametrization of the chargino vertices. The rôle of the $b \to s\gamma$ constraint is illustrated in Fig. 4 (with due attention to the uncertainty in the theoretical prediction [25]).

The second important remark is that the element $V_{td} \approx A\lambda^3(\rho - i\eta)$ (in the Wolfenstein parametrization), which is necessary for the calculation of the chargino and charged Higgs boson loops to the ε parameter and the $\overline{B}^0 - B^0$ mixing, is not directly measured. Its SM value can change after the inclusion of new contributions. Thus the correct approach is the following one: take *e.g.*

$$\Delta m_B \approx f^2_{B_d} B_{B_d} |V_{tb}V^*_{td}|^2 |\Delta| , \tag{8}$$

where

$$\Delta = \Delta_W + \Delta_{NEW} \tag{9}$$

is the sum of all box diagram contributions, f_{B_d} and B_{B_d} are the B^0 meson decay constant and the vacuum saturation parameter. The CP violating parameter ε can also be expressed in terms of Δ. Given $|V_{cb}|$, and $|V_{ub}/V_{cb}$ (known from the the tree level processes *i.e.* almost unaffected by the supersymmetric contributions) one can fit the parameters ρ, η and Δ to the experimental values of Δm_{B_d} and $|\varepsilon_K|$. This way we find [26, 27] a model independent constraint

$$\frac{\Delta}{\Delta_W} < 3 \tag{10}$$

for $\sqrt{f^2_{B_d} B_{B_d}}$ in the range $(160 - 240)$ GeV and B_K in the range $(0.6 - 0.9)$ GeV, which in the next step can be used to limit the allowed range of the stop and chargino masses and mixings. The contours of Δ values for the parameters of Fig. 4 are shown in Fig. 6 [28]. We see that the parameter space which is relevant for an increase in R_b gives large contribution to Δ. It is still consistent with the data on rare processes but requires modified (compared to the SM) values of the CP-violating phase δ (η, ρ).

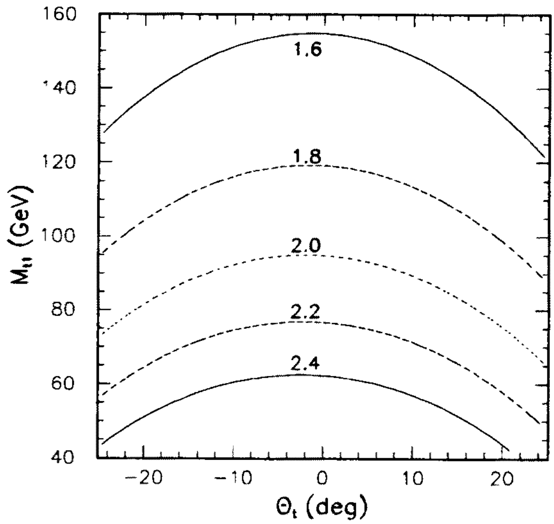

Fig. 6. Contours of constant Δ/Δ_W (see the text) in the plane $(\theta_t, M_{\tilde{t}_1})$ for the same set of parameters as in Fig.4.

3. R_b anomaly and exotic events

A single event $e^+e^-\gamma\gamma+$missing E_T has been reported by Fermilab [6]. Preliminary results from the LEP1.5 run (after the upgrade of energy to $\sqrt{s} = 130 - 136$ GeV) include peculiar four-jet events reported by ALEPH [5]. Although statistics is too low to exclude fluctuations, it is interesting to speculate if they can be explained by supersymmetry and whether simultaneous explanation of these events and the R_b anomaly is possible. A detailed study of the Fermilab event in the supersymmetric extension of the SM is a subject of Refs [29]. It is interesting to observe that the Fermilab event can be explained as a selectron pair production, with the supersymmetric spectrum which is consistent with larger than in the SM values of R_b. The best description is obtained for $M_1 \approx M_2$ but in a model with $R-$parity conservation. This last fact should be stressed in view of the following discussion of ALEPH events.

ALEPH 4-jet events have very peculiar gross features. On the kinematical grounds they can be interpreted as a production of a pair of new particles X with $m_X \approx 55$ GeV and a relatively large effective (after cuts) production cross section $\sigma \approx 3.7 \pm 1.7$ pb. Any interpretation of this new particle is strongly constrained by the decay signature: to a good approximation no missing energy has been observed and most of the events do not contain identified $b-$quark jets and no fast leptons in the final state. Those signatures of the events imply that any explanation within a $R-$parity conserving MSSM is very difficult (for an explanation based on the idea of a light gluino, $m_{\tilde{g}} \sim 1$ GeV see Ref. [30]). Moreover, a large production cross section is not easy to accomodate ($R-$parity violation has little impact on the production cross section so it can be reliably estimated in the MSSM). A sneutrino pair production seems to be an acceptable possibility [31] but its connection to the R_b anomaly is not obvious. Turning now to supersymmetric fermions, a neutralino of a mass 55 GeV has production cross section more than one order of magnitude below the reported value. Thus, we are left with a light chargino as the most interesting candidate to explain ALEPH events. Indeed, the full production cross section are typically large $\mathcal{O}$(10pb) (see Fig. 7). Moreover, there is an interesting link with R_b anomaly.

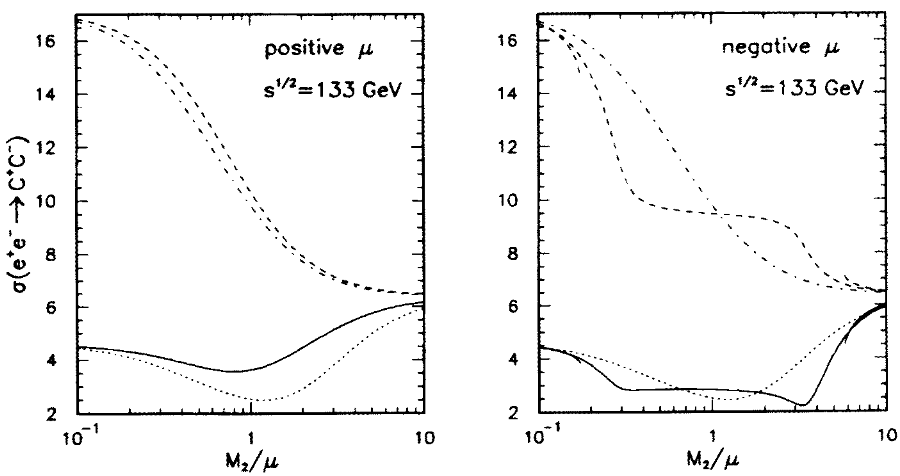

Fig. 7. Cross sections for 55 GeV chargino production for different choices of $(\tan\beta, M_{\tilde{\nu}_e})$ values: for $\mu > 0$: (1.4 50)-solid, (1.4,200)-dashed, (50,50)-dotted, (50,200)-dashdotted; for $\mu < 0$: (1.8, 50)-solid, (1.8,200)-dashed, (50,50)-dotted, (50,200)-dash-dotted.

The question which remains is whether chargino decay signatures can be consistent with ALEPH data. No missing energy rules out $R-$parity conserving schemes. If $R-$parity is not conserved, additional terms in the superpotential are allowed

$$W = \tfrac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \tfrac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k\,, \qquad (11)$$

where $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$. The first two terms violate lepton number conservation and the last one — baryon number conservation.

Simultaneous presence of both types of terms can lead to rapid proton decay. Only λ and λ' or $\lambda''-$type couplings are allowed, of course within the present experimental limits. The latter depend on the type of the coupling but for several of them are relatively weak, particularly for the couplings involving the third family.

If the chargino decay through a lepton number violating coupling, there should be a hard lepton or missing momentum in the event. Thus this explanation looks unlikely. With baryon number violating couplings λ'', the chargino may decay via either of two channels

$$C^{\pm} \to \tilde{q}_1^* q_2 \to q_2 q_3 q_4 \,, \tag{12}$$

where the squark is right handed and can be virtual, and

$$\begin{aligned} C^{\pm} \to N^{0*} W^{\pm *} \to & N^{0*} f_1 f_2 \\ & \hookrightarrow q_3 q_4 q_5 \end{aligned} \tag{13}$$

with N^0 real or virtual. The actual decay pattern depends on the details of the couplings and the values of the masses. However, with most natural assumptions, that right stop is the lightest squark and that the coupling λ''_{tds} is the largest one, we can see already at the qualitative level that it is not easy to reproduce experimental decay signatures. We expect in this scenario too many jets and/or $b-$quark jets and/or hard leptons in the final state. One remarkable exception is the possibility $m_{C^-} \gtrsim M_{\tilde{t}_R} \approx 55$ GeV and with both masses close to each other. Then ALEPH events can be explained by [32]

$$Z^0 \to C^- C^+ \to (\tilde{t}_R \bar{b})(\bar{\tilde{t}}_R b) \to (\bar{d}\bar{s}\bar{b})(dsb) \tag{14}$$

with very slow $b-$quarks and therefore escaping detection. With the present experimental resolution, a mass degeneracy $m_{C^-} - M_{\tilde{t}_R} \approx (5 - 12)$ GeV is sufficient for this scenario [32]. Neutralino could still be light but the decay $C^- \to N^0 f_1 f_2$ is suppressed due to kinematical reasons (due to multibody final states). A link with the R_b anomaly is clear. However, simultaneous supersymmetric explanation of the Fermilab (one) event and the ALEPH 4$-$jet events looks unlikely because of the need for broken $R-$parity in the latter case.

4. Conclusions

Chargino and right handed stop are likely to be (in addition to neutralinos) the lightest supersymmetric particles. Not only the masses in the range or even below M_Z are not excluded by any presently available experimental data, they may be responsible for the R_b puzzle. Depending on whether $R-$parity is conserved or not, the Fermilab event or ALEPH events may be explained simultaneously with large values of R_b. In particular, ALEPH events, if confirmed, may signal the discovery of a chargino with $m_C \approx 60$ GeV, a stop with $M_{\tilde{t}} \approx 55$ GeV and broken $R-$parity.

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