KA–TP–23–1997

Electroweak Precision Observables in the MSSM and Global Analyses of Precision Data*

W. Hollik

Institut für Theoretische Physik
Universität Karlsruhe
D-76128 Karlsruhe, Germany

Abstract

The calculation of electroweak precision observables in the MSSM is reviewed. The description of the data of 1997 and results of updated global fits are discussed in comparison with the Standard Model.

*talk given at the International Workshop on Quantum Effects in the MSSM, Barcelona, 9 - 13 September 1997

ELECTROWEAK PRECISION OBSERVABLES IN THE MSSM AND GLOBAL ANALYSES OF PRECISION DATA

W. HOLLIK
Institut für Theoretische Physik, Universität Karlsruhe
D-76128 Karlsruhe, Germany
E-mail: Wolfgang.Hollik@physik.uni-karlsruhe.de

The calculation of electroweak precision observables in the MSSM is reviewed. The description of the 1997 data and the results of updated global fits are discussed in comparison with the Standard Model.

1 Introduction

Experiments have measured the electroweak observables of the W and Z bosons [1] and the top quark [2] with an impressive accuracy thus providing precision tests of the electroweak theory at a level which had never been reached before. The description of the current precision data by the minimal Standard Model is extaordinarily successful, with a few observed deviations of the order $\geq 2\sigma$. They lower the quality of the Standard Model fits, but they can be understood as fluctuations statistically normal.

Extensions of the Standard Model hence are essentially theoretically motivated. Among the supersymmetric extensions, the R-parity conserving minimal supersymmetric standard model (MSSM) with the minimal particle content plays a special role as the most predictive framework beyond the Standard Model. Besides introducing the superpartners for the standard particles, the Higgs sector has to be augmented by a second scalar doublet. The structure of the MSSM allows a similarly complete calculation of the electroweak precision observables as in the Standard Model in terms of one Higgs mass and the ratio v_2/v_1 of the Higgs vacua together with the set of SUSY soft breaking parameters fixing the chargino/neutralino and scalar fermion sectors. Besides the direct searches for SUSY particles, which as yet have not been successful [3], the interest for indirect tests of the MSSM in terms of virtual effects from the non-standard particles has triggered a broad activity in calculating and investigating the supersymmetric quantum effects in the electroweak precision observables [4,5,6,7,8]. Complete one-loop calculations are available for the quantity Δr in the M_W-M_Z correlation [6] and for the Z boson observables [7,8] and have recently been improved by the supersymmetric QCD corrections to the ρ-parameter at the two-loop level [9].

2 MSSM entries

The quantum contributions to the electroweak precision observables contain, besides the standard input, the following entries:

Higgs sector: The scalar sector of the MSSM, consisting of three neutral particles h^0, H^0, A^0 and a pair of charged bosons $H^\pm$, is completely determined by the value of $\tan\beta = v_2/v_1$ and the pseudoscalar mass M_A, together with the radiative corrections. The latter ones can be easily taken into account by means of the effective potential approximation with the leading terms $\sim m_t^4$, including mixing in the scalar top system [10]. In this way, the coupling constants of the various Higgs particles to gauge bosons and fermions can be taken from [11] substituting only the scalar mixing angle α by the improved effective mixing angle which is obtained from the diagonalization of the scalar mass matrix. The mass of the light h^0 is constrained to $<$ 130 GeV when the dominant two-loop corrections are included [12].

Chargino/Neutralino sector: The chargino (neutralino) masses and the mixing angles in the gaugino couplings are calculated from soft breaking parameters M_1, M_2 and μ in the chargino (neutralino) mass matrix [11]. For practical calculations, the GUT relation $M_1 = 5/3 \tan^2\theta_W\, M_2$ is conventionally assumed.

The chargino 2×2 mass matrix is given by

$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & M_W\sqrt{2}\sin\beta \\ M_W\sqrt{2}\cos\beta & -\mu \end{pmatrix} , \qquad (1)$$

with the SUSY soft breaking parameters μ and M_2 in the diagonal matrix elements. The physical chargino mass states $\tilde{\chi}_i^\pm$ are the rotated wino and charged Higgsino states:

$$\begin{aligned} \tilde{\chi}_i^+ &= V_{ij}\psi_j^+ \\ \tilde{\chi}_i^- &= U_{ij}\psi_j^- \;;\; i,j = 1,2 . \end{aligned} \qquad (2)$$

V_{ij} and U_{ij} are unitary chargino mixing matrices obtained from the diagonalization of the mass matrix Eq. (1):

$$\mathrm{U}^*\mathcal{M}_{\tilde{\chi}^\pm}\mathrm{V}^{-1} = \mathrm{diag}(\mathrm{m}_{\tilde{\chi}_1^\pm}, \mathrm{m}_{\tilde{\chi}_2^\pm}) . \qquad (3)$$

The neutralino 4×4 mass matrix $\mathcal{M}_{\tilde{\chi}^0}$ can be written as:

$$\begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & \mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & \mu & 0 \end{pmatrix} \tag{4}$$

where the diagonalization can be obtained by the unitary matrix N_{ij}:

$$\mathrm{N}^* \mathcal{M}_{\tilde{\chi}^0} \mathrm{N}^{-1} = \mathrm{diag}(\mathrm{m}_{\tilde{\chi}^0_i}) \ . \tag{5}$$

The elements U_{ij}, V_{ij}, N_{ij} of the diagonalization matrices enter the couplings of the charginos, neutralinos and sfermions to fermions and gauge bosons, as explicitly given in ref. [11]. Note that the sign convention on the parameter μ is opposite to that of ref. [11].

Sfermion sector: The physical masses of squarks and sleptons are given by the eigenvalues of the 2×2 mass matrix: $\mathcal{M}^2_{\tilde{\mathrm{f}}} =$

$$\begin{pmatrix} M^2_{\tilde{Q}_L} + m_f^2 + M_Z^2 (I_3^f - Q_f s_W^2) \cos 2\beta & m_f (A_f + \mu\{\cot\beta, \tan\beta\}) \\ m_f (A_f + \mu\{\cot\beta, \tan\beta\}) & M^2_{\{\tilde{U},\tilde{D}\}_R} + m_f^2 + M_Z^2 Q_f s_W^2 \cos 2\beta \end{pmatrix} , \tag{6}$$

with SUSY soft breaking parameters $M_{\tilde{Q}_L}$, $M_{\tilde{U}_R}$, $M_{\tilde{D}_R}$, A_f, and μ. It is convenient to use the following notation for the off-diagonal entries in Eq. (6):

$$M_f^{LR} = A_f + \mu\{\cot\beta, \tan\beta\} \ . \tag{7}$$

Scalar neutrinos appear only as left-handed mass eigenstates. Up and down type sfermions in (6) are distinguished by setting f=u,d and the corresponding $\{u, d\}$ entries in the parenthesis. Since the non-diagonal terms are proportional to m_f, it seems natural to assume unmixed sfermions for the lepton and quark case except for the scalar top sector. The $\tilde{t}$ mass matrix is diagonalized by a rotation matrix with a mixing angle $\theta_{\tilde{t}}$. Instead of $M_{\tilde{Q}_L}$, $M_{\tilde{t}_R}$, $M_{\tilde{b}_R}$, M_t^{LR} for the $\tilde{b}$, $\tilde{t}$ system ($Q = t, b$) the physical squark masses $m_{\tilde{b}_L}, m_{\tilde{b}_R}$, $m_{\tilde{t}_2}$ can be used together with M_t^{LR} or, alternatively, the stop mixing angle $\theta_{\tilde{t}}$. For simplicity one may assume $m_{\tilde{b}_L} = m_{\tilde{b}_R}$, and $\tilde{u}$, $\tilde{d}$, $\tilde{c}$, $\tilde{s}$ to have masses equal to the $\tilde{b}$ squark mass. The labels for the $\tilde{t}$ mass eigenstates are chosen in such a way that one gets $\tilde{t}_1 = \tilde{t}_L$, $\tilde{t}_2 = \tilde{t}_R$ for the case of zero mixing.

3 Precision observables

3.1 The ρ-parameter

A possible mass splitting between the left-handed components of the $\tilde{b}$ and $\tilde{t}$ system yields a contribution to the ρ-parameter $\rho = 1 + \Delta\rho$ in terms of (neglecting left-right mixing in the $\tilde{b}$ sector)

$$\Delta\rho_{\tilde{t}\tilde{b}} = \frac{3G_\mu}{8\pi^2\sqrt{2}} \Big[\cos^2\theta_{\tilde{t}}\, F_0(m^2_{\tilde{t}_1}, m^2_{\tilde{b}_L}) + \sin^2\theta_{\tilde{t}}\, F_0(m^2_{\tilde{t}_2}, m^2_{\tilde{b}_L}) \\ - \sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{t}}\, F_0(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})\Big]$$

$$\text{with} \quad F_0(x,y) = x + y - \frac{2xy}{x-y}\log\frac{x}{y} \tag{8}$$

Examples for $\Delta\rho$ from the squark loops of the third generation, which can become remarkably large, are displayed in Figure 1. Recently the 2-loop α_s corrections have been computed [9,13] which can amount to a sizeable fraction of the 1-loop $\Delta\rho_{\tilde{b}\tilde{t}}$. As a universal loop contribution, $\Delta\rho_{\tilde{t}\tilde{b}}$ enters the quantity Δr and the Z boson couplings through the relations (9) and (11) and is thus significantly constrained by the data on M_W and the leptonic Z widths.

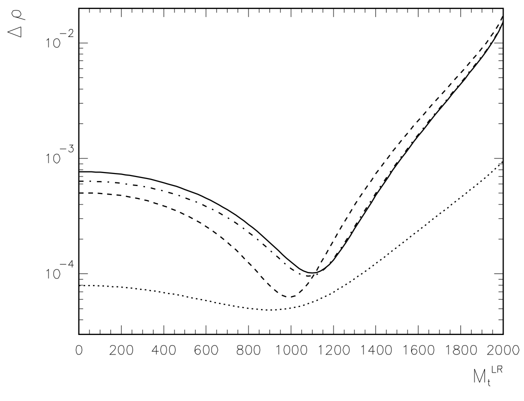

Figure 1: $\Delta\rho_{\tilde{t}\tilde{b}}$ for $\tan\beta = 1.6$. $M_{\tilde{t}_L}/M_{\tilde{t}_R} = 1000/300$ (dotted), $300/1000$ (solid)

3.2 The vector boson masses

The correlation between the masses M_W, M_Z of the vector bosons in terms of the Fermi constant G_μ in is given by

$$
\begin{aligned}
\frac{G_\mu}{\sqrt{2}} &= \frac{\pi\alpha}{2 s_W^2 M_W^2} \cdot \frac{1}{1-\Delta r} \\
&= \frac{\pi\alpha}{2 s_W^2 M_W^2} \cdot \frac{1}{(1-\Delta\alpha)\cdot(1+\frac{c_W^2}{s_W^2}\Delta\rho) \;-\; (\Delta r)_{\rm rem}}
\end{aligned}
\tag{9}
$$

$$
\text{with} \quad s_W^2 = 1 - \frac{M_W^2}{M_Z^2}\,.
$$

Therein, $\Delta\alpha = 0.0595 \pm 0.0007$ [14] is the QED vacuum polarization of the photon from the light fermions, $\Delta\rho$ is the irreducible quantum contribution to the ρ-parameter, and $(\Delta r)_{\rm rem}$ contains the residual loop terms. Complete 1-loop calculations for the quantity Δr have been performed in ref's [6]. Besides the higher order contributions beyond 1-loop from the Standard Model (see [15] for more information and references), the SUSY-QCD 2-loop terms to $\Delta\rho$ are meanwhile available, as mentioned above in Section 3.1, as well as the complete 2-loop gluonic QCD corrections to the squark loop contributions to Δr [13]. The SUSY QCD corrections to Δr are well approximated by the SUSY QCD corrections to $\Delta\rho$. The 2-loop terms correspond to a shift in the W mass of 10-20 MeV for not too heavy SUSY partners of the quarks and are thus of phenomenological importance.

By Eq. (9) the value for M_W is fixed when M_Z is taken as input and the MSSM model parameters have been chosen. Figure 2 displays the range of predictions for M_W in the Standard Model (SM) and in the MSSM. Thereby it is assumed that no direct discovery has been made at LEP2 for constraining the model parameters. As one can see, precise determinations of M_W and m_t can become decisive for the separation between the models. The present world average [1] $M_W = 80.43 \pm 0.08$ GeV together with [2] $m_t = 175.6 \pm 5.5$ GeV shows a slight, but not significant, preference for the MSSM.

3.3 Z boson observables

With M_Z as a precise input parameter, the predictions for the partial widths as well as for the asymmetries can conveniently be calculated in terms of effective neutral current coupling constants for the various fermions entering the neutral

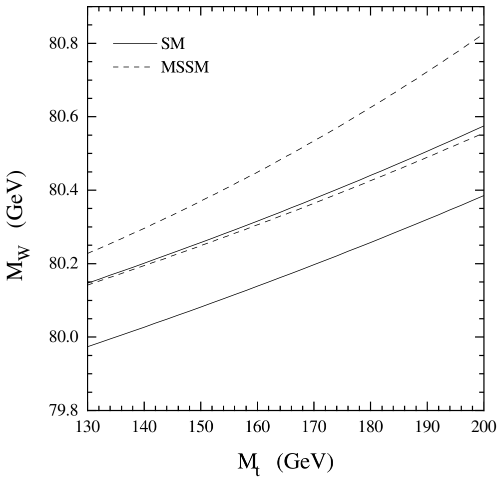

Figure 2: The W mass range in the Standard Model (——) and the MSSM (- - -). Bounds are from the non-observation of Higgs bosons and SUSY particles at LEP2.

current vertex as follows:

$$\begin{aligned} J_\nu^{\rm NC} &= g_V^f\,\gamma_\nu - g_A^f\,\gamma_\nu\gamma_5 \\ &= (\rho_f)^{1/2}\left[(I_3^f - 2Q_f\,s_f^2)\gamma_\nu - I_3^f\,\gamma_\nu\gamma_5\right] \end{aligned} \tag{10}$$

with form factors ρ_f for the overall normalization and with the effective mixing angles $s_f^2 = \sin^2\theta_f$ for the corresponding fermions. The leading universal terms associated with the ρ-parameter enter the Z boson couplings through

$$\begin{aligned} \rho_f &= \frac{1}{1-\Delta\rho} + \cdots \\ s_f^2 &= s_W^2 + c_W^2\,\Delta\rho + \cdots \end{aligned} \tag{11}$$

Large non-universal contributions from the Higgs and the genuine SUSY particle sector are possible especially for the b-quark couplings.

Asymmetries and mixing angles:
The effective mixing angles are of particular interest since they determine the on-resonance asymmetries via the combinations

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}\,. \tag{12}$$

Measurements of the asymmetries hence are measurements of the ratios

$$g_V^f/g_A^f = 1 - 2Q_f s_f^2 \tag{13}$$

or of the effective mixing angles s_f^2.
The measurable quantities are:
– the forward-backward asymmetries in $e^+e^- \to f\bar{f}$:

$$A_{\mathrm{FB}}^f = \frac{3}{4} A_e \cdot A_f$$

– the left-right asymmetry:

$$A_{\mathrm{LR}} = A_e$$

– the τ polarization in $e^+e^- \to \tau^+\tau^-$:

$$P_\tau = A_\tau \,.$$

It is interesting to note that the non-standard loop contributions to the leptonic mixing angle s_e^2 diminish the Standard Model value. A small experimental value, as observed in A_{LR}, could therefore be accomodated in the MSSM also for a relatively high top mass.

Z widths and cross sections: The total Z width Γ_Z can be calculated essentially as the sum over the fermionic partial decay widths:

$$\Gamma_Z = \sum_f \Gamma_f, \quad \Gamma_f = \Gamma(Z \to f\bar{f})\,. \tag{14}$$

The peak cross sections for $e^+e^- \to f\bar{f}$ (had) are determined by

$$\sigma_0^f = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}, \quad \sigma_0^{\mathrm{had}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma_Z^2}\,. \tag{15}$$

The partial widths, expressed in terms of the effective coupling constants, read up to 2nd order in the fermion masses:

$$\Gamma_f = \Gamma_0 \left((g_V^f)^2 + (g_A^f)^2 (1 - \frac{6m_f^2}{M_Z^2}) \right) \cdot (1 + Q_f^2 \frac{3\alpha}{4\pi}) + \Delta\Gamma_{QCD}^f$$

with

$$\Gamma_0 \;=\; N_C^f \frac{\sqrt{2} G_\mu M_Z^3}{12\pi}, \quad N_C^f = 1 \text{ (leptons)}, \;\; = 3 \text{ (quarks)}.$$

and the QCD corrections $\Delta\Gamma^f_{QCD}$ for quark final states, both from standard (see [15] for references) and SUSY QCD. The gluino contribution, however, is very small.

Of particular interest is the quantity

$$R_{\mathrm{b}} = \frac{\Gamma_{\mathrm{b}}}{\Gamma_{\mathrm{had}}} \tag{16}$$

which in the Standard Model is most sensitive to the mass of the top quark. As already known for quite some time [4], light non-standard Higgs bosons for large $\tan\beta$ as well as light stop and charginos influence the b-quark couplings remarkably and predict larger values for the ratio R_b in the MSSM [5,7] (see figures 3, 4).

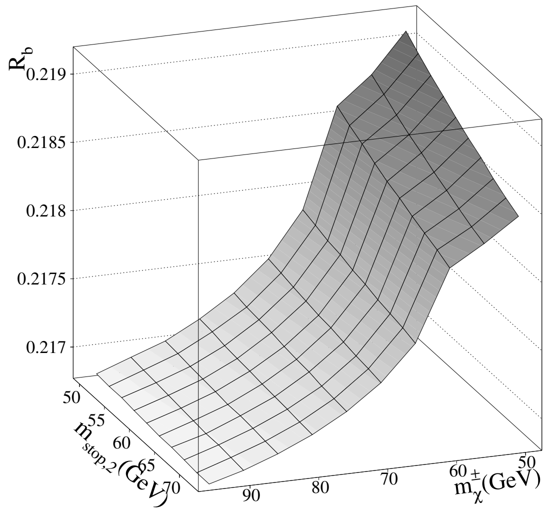

Figure 3: R_b in the light stop-chargino plane. $\tan\beta = 1.6$. [8]

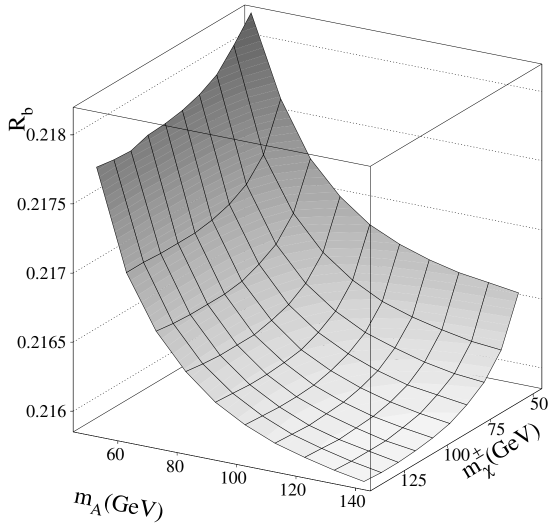

Figure 4: R_b in the pseudoscalar Higgs - chargino plane. $\tan\beta = 34$. [8]

4 MSSM global fits to precision data

For obtaining the optimized SUSY parameter set a global fit to all the electroweak precision data, including the top mass measurement, has to be performed. Two strategies can be persued: (i) the parameters of the MSSM are further restricted by specific model assumptions like unification scenarios, or (ii) the MSSM parameters are considered as free quantitites chosen in the optimal way for improving the observed deficiencies of the Standard Model in describing the data. (ii) has been applied in [8], recently updated by Schwickerath [16]. In the past, the experimental value of $R_{\rm b}$ was 3.7σ away from the Standard Model predictions and could be accomodated much better in MSSM scenarios with light stop and charginos and/or light scalar amd pseudoscalar Higgs bosons. In the meantime, $R_{\rm b}$ has decreased and is now much closer to the Standard Model value. Instead, $A_{\rm FB}^{\rm b}$ shows a 2σ deviation between data and Standard Model prediction [1].

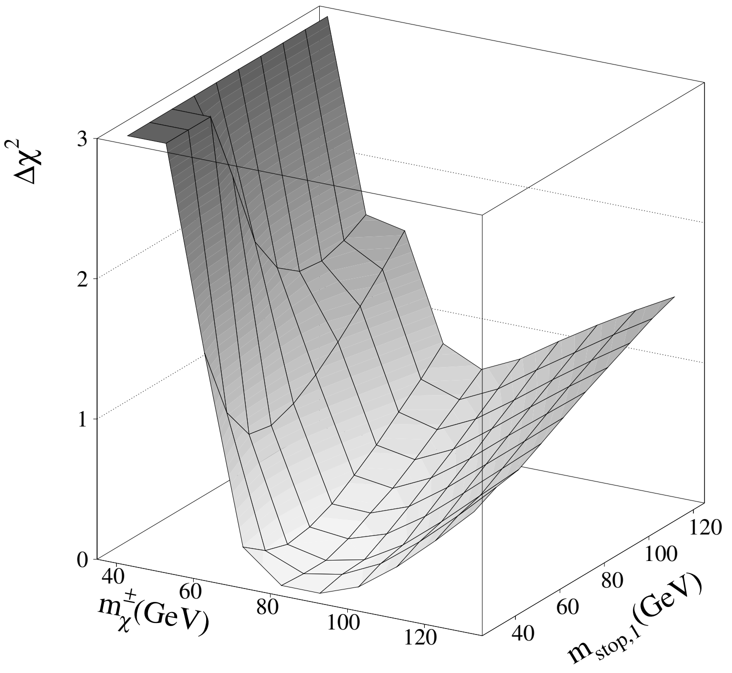

Figure 5: $\Delta\chi^2$ for $\tan\beta = 1.5$. No limits for supersymmetric particle masses are imposed (from [8] updated in [16])

In order to obtain the best MSSM fits the electroweak precision data are taken into account together with the error correlations [1], and the measurement of the branching ratio $R_{b\to s\gamma} = \mathrm{BR}(B \to X_s\gamma)$ by CLEO and ALEPH [17] with the combined value $(2.55 \pm 0.61)\cdot 10^{-4}$. The $b \to s\gamma$ rate becomes too small if $\tan\beta$ is near one. For $\tan\beta = 1.6$ and 35, MSSM solutions can be found which are compatible with $R_{b\to s\gamma}$ and the electroweak precision data. For the MSSM calculation of $R_{b\to s\gamma}$, the results of [18] are used with a chosen renormalization scale of $\mu = 0.65 m_b$.

For reducing the large number of parameters, the simplifying assumptions described in Section 2 are applied. As a common squark mass scale the value $M_{\tilde{Q}} = 1$ TeV is chosen; $M_{\tilde{t}_R}$ and the stop mixing angle $\theta_{\tilde{t}}$ are kept free to allow for a light stop state $\tilde{t}_2$. This state has to be predominatly right-handed to avoid deteriorations of the ρ-parameter according to Eq. (8). In the slepton sector, common masses of 0.5 TeV are assumed for both left and right-handed components neglecting left-right mixing. The fits are insensitive to the detailed values of the heavy particles. Figure 5 shows the increase of the χ^2 of the fit [16] in the light stop-chargino plane ($\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$). In each point, the parameters $m_t, \alpha_s, \theta_{\tilde{t}}, M_2$ are optimized.

Table 1: Fitted parameters and mass spectrum for the best low and high $\tan\beta$ fits [16], updated from [8]. Parameter values in brackets are not fitted, but fixed to the given value during the fit.

	$\tan\beta$=1.5	$\tan\beta$=35
χ^2/d.o.f.	15.0/13	15.8/13
prob.	31%	26%
fitted parameters		
$\alpha_s(M_Z^2)$	0.1161	0.1196
m_t [GeV]	174.0	174.3
M_2 [GeV]	68	(1500)
μ [GeV]	79	92
m_A [GeV]	(1500)	60
$m_{\tilde{t}_2}$ [GeV]	80	81
$\theta_{\tilde{t}}$	-0.139	0.0126
mass spectrum		
$\tilde{\chi}_1{}^{\pm}$,$\tilde{\chi}_2{}^{\pm}$ [GeV]	89, 126	92, 1504
$\tilde{\chi}_1{}^0$,$\tilde{\chi}_2{}^0$[GeV]	38,70	89,96
$\tilde{\chi}_3{}^0$,$\tilde{\chi}_4{}^0$[GeV]	115,123	716,1504
$m_{\tilde{t}_1}$ [GeV]	1023	1012
M_h, M_H [GeV]	98,1503	60,103
$M_{H^\pm}$ [GeV]	1502	124
M_W [GeV]	80.42	80.43

Constraints from direct searches for SUSY particles [3] can be taken into account with the help of a penalty function (see [16]): $M_A > 50$ GeV, $M_h > 60$ GeV, $m_{\tilde{\chi}^+} > 85$ GeV, $m_{\tilde{t}_2} > 80$ GeV. With these constraints the best fit results for a low and high $\tan\beta$ scenario are listed in Table 1. The values of the strong coupling constant α_s is close to the best fit value of the Standard Model [1] $\alpha_s(\rm SM) = 0.120 \pm 0.003$. For the low $\tan\beta$ scenario α_s is slightly lower; this is due to the positive loop contribution to the partial Z width $\Gamma_{\rm b}$, which is less pronounced in the high $\tan\beta$ scenario because of the constraints to the Higgs masses. The particle spectrum for the best fits suggests that some SUSY particles could be within reach of LEP 2; the χ^2 in the region of the best low $\tan\beta$ fit, however, increases only slowly for increasing chargino masses. Within the high $\tan\beta$ scenario both neutral h^0, A^0 bosons are light and have practically the same mass. This scenario can be excluded if no Higgs bosons will be found at LEP 2.

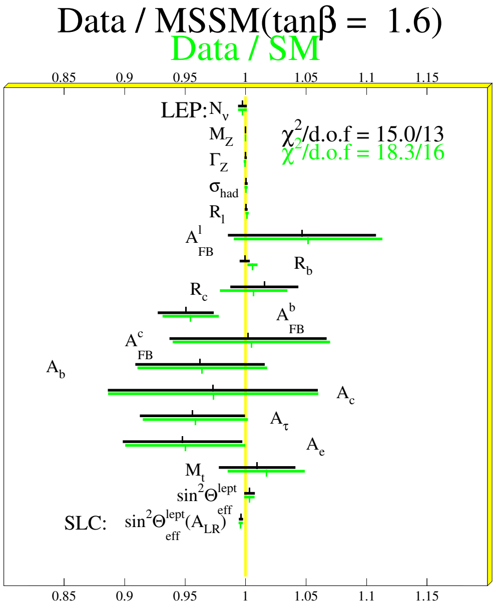

Figure 6: Experimental data normalized to the best fit results in the SM and MSSM for low $\tan\beta$, with experimental error bars (updated from [8] in [16]).

A direct comparison to the Standard Model fit is shown in Figure 6 for $\tan\beta = 1.6$. A very similar plot is obtained for $\tan\beta = 35$ displayed in Figure 7. The present small difference between the experimental and the SM value of R_b can be completely removed in the MSSM for the low $\tan\beta$. Other quantities are practically unchanged; in particular, the difference between data and theory observed in A^b_{FB} cannot be significantly diminished. The χ^2 of the MSSM fits are lower than in the Standard Model, but due to the larger number of parameters the probability in the MSSM is not higher than in the

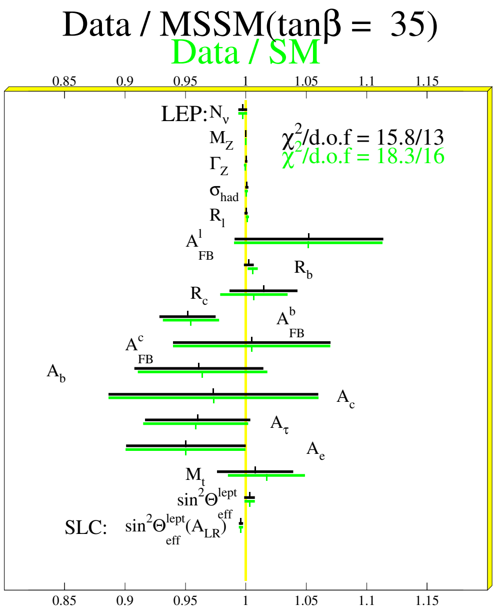

Figure 7: Experimental data normalized to the best fit results in the SM and MSSM for high $\tan\beta$, with experimental error bars (updated from [8] in [16]).

Standard Model (31%); for high $\tan\beta$ the probability is even lower. (The small difference to the SM result of the LEP Electroweak Working Group is due to the inclusion of $R_{b\to s\gamma}$ in our fit.) This means that the MSSM yields an equally good description of the data as the minimal Standard Model and is thus competitive, but it does not appear as superior.

5 Conclusions

The supersymmetric extension of the Standard Model realized in terms of the MSSM permits a similar complete calculation of the electroweak precision observables as in the Standard Model. The version with all SUSY particles and the $A^0, H^0, H^\pm$ Higgs bosons heavy is equivalent to the Standard Model with a light Higgs around 120 GeV. The possibility of having some of the non-standard particles light, in the mass range around 100 GeV, opens the option to remove some of the observed deviations between data and theory, like in R_b. The overall χ^2 of a global fit is therefore slightly lower than in a corresponding

Standard Model fit; the larger number of parameters, however, reduce the χ^2 per degree of freedom and thus the probability of the MSSM to that of the Standard Model. The MSSM thus yields an equally good description of the precision data as the Standard Model. It is always possible to worsen the fits by inappropriate choices of the model parameters, which can be used to exclude certain regions of the parameter space, as done recently in [19]. The W mass predicted by the MSSM is always higher than in the Standard Model; present data show a slightly better agreement with the MSSM. From the increasing experimental accuracy for M_W and m_t in the future one hence expects a very important probe for both the Standard Model and the MSSM.

References

1. The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavor Working Group, CERN-PPE/96-183 (1996); for the update see:
   J. Timmermans, Proceedings of the *XVIII International Symposium on Lepton-Photon Interactions*, Hamburg 1997;
   D. Ward, Proceedings of the *International Europhysics Conference on High Energy Physics*, Jerusalem 1997
2. P. Giromini, Proceedings of the *XVIII International Symposium on Lepton-Photon Interactions*, Hamburg 1997
3. P. Janot, Proceedings of the *International Europhysics Conference on High Energy Physics*, Jerusalem 1997
4. A. Denner, R. Guth, W. Hollik, J.H. Kühn, *Z. Phys.* C **51** (1991) 695;
   J. Rosiek, *Phys. Lett.* B **252** (1990) 135;
   M. Boulware, D. Finnell, *Phys. Rev.* D **44** (1991) 2054
5. G. Altarelli, R. Barbieri, F. Caravaglios, *Phys. Lett.* B **314** (1993) 357;
   C.S. Lee, B.Q. Hu, J.H. Yang, Z.Y. Fang, *J. Phys.* G **19** (1993) 13;
   Q. Hu, J.M. Yang, C.S. Li, *Comm. Theor. Phys.* **20** (1993) 213;
   J.D. Wells, C. Kolda, G.L. Kane, *Phys. Lett.* B **338** (1994) 219;
   G.L. Kane, R.G. Stuart, J.D. Wells, *Phys. Lett.* B **354** (1995) 350;
   M. Drees et al., *Phys. Rev.* D **54** (1996) 5598;
   J. Ellis, G. Fogli. E. Lisi, *Phys. Lett.* B **389** (1996) 321
6. P. Chankowski, A. Dabelstein, W. Hollik, W. Mösle, S. Pokorski, J. Rosiek, *Nucl. Phys.* B **417** (1994) 101;
   D. Garcia, J. Solà, *Mod. Phys. Lett.* A **9** (1994) 211
7. D. Garcia, R. Jiménez, J. Solà, *Phys. Lett.* B **347** (1995) 309; B **347** (1995) 321; D. Garcia, J. Solà, *Phys. Lett.* B **357** (1995) 349;
   A. Dabelstein, W. Hollik, W. Mösle, in *Perspectives for Electroweak In-*

teractions in e^+e^- Collisions, Ringberg Castle 1995, Ed. B.A. Kniehl, World Scientific 1995 (p. 345);
P. Chankowski, S. Pokorski, *Nucl. Phys.* B **475** (1996) 3
8. W. de Boer, A. Dabelstein, W. Hollik, W. Mösle, U. Schwickerath, *Z. Phys.* C **75** (1997) 627
9. A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. Weiglein, *Phys. Rev. Lett.* **78** (1997) 3626; – hep-ph/9710438
10. J. Ellis, G. Ridolfi and F. Zwirner, *Phys. Lett.* B **257** (1991) 83
11. H. P. Nilles, *Phys. Rep.* **110** (1984) 1;
H. E. Haber, G. Kane, *Phys. Rep.* **117** (1985) 75;
J. F. Gunion, H. E. Haber, *Nucl. Phys.* B **272** (1986) 1;
Nucl. Phys. B **402** (1993) 567;
J. F. Gunion, H. E. Haber, G. Kane, S. Dawson: *The Higgs Hunter's Guide,* Addison-Wesley 1990.
12. R. Hempfling, A. Hoang, *Phys. Lett.* B **331** (1994) 99;
M Carena, M. Quiros, C. Wagner, *Nucl. Phys.* B **461** (1996) 407
13. S. Heinemeyer, *2-Loop Calculations in the MSSM*, these Proceedings
14. S. Eidelman, F. Jegerlehner, *Z. Phys.* C **67** (1995) 585;
H. Burkhardt, B. Pietrzyk, *Phys. Lett.* B **356** (1995) 398
15. W. Hollik, *Review Status of the Standard Model*, these Proceedings
16. U. Schwickerath, Proceedings of the *XVI International Workshop on Weak Interactions and Neutrinos (WIN'97)*, Capri 1997
17. CLEO-Collaboration, R. Ammar et al., *Phys. Rev. Lett.* **74** (1995) 2885;
M. Feindt, Proceedings of the *International Europhysics Conference on High Energy Physics*, Jerusalem, August 1997 (to appear)
18. R. Barbieri, G. Giudice, *Phys. Lett.* B **309** (1993) 86;
R. Garisto, J.N. Ng, *Phys. Lett.* B **315** (1993) 372;
S. Bertolini, F. Borzumati, A.Masiero, G. Ridolfi, *Nucl. Phys.* B **353** (1991) 591 *and references therein*;
N. Oshimo, *Nucl. Phys.* B **404** (1993) 20;
S. Bertolini, F. Vissani, *Z. Phys.* C **67** (1995) 513, 1995
19. D.M. Pierce, J. Erler, hep-ph/9708374