Could stops lighten the top?

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Abstract

Analysis of the presently available electroweak data including radiative corrections in the Standard Model suggests that the top quark weighs more than the Z^0 . We examine whether squark loops in the minimal supersymmetric model, particularly those involving stops (partners of the top quark), could reduce substantially the preferred range of top quark masses. Given the present lower bounds on squark masses, we find that stop effects can reduce the central value of m_t by at most a few GeV, although they do make a very heavy top quark increasingly unlikely.

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CERN-TH. 5749/90

May 1990

and to the quantity Δr (i.e. to the μ -decay rate) has been performed in [10], with an estimate of all the contributions coming from superpartner (gaugino/higgsino and smatter) self-energies, from box diagrams and from vertex corrections, and a discussion of the relative importance of the different terms.

Although all these supersymmetric contributions have been calculated analytically and numerically, they have not been included in a global analysis of electroweak data. Such an exercise is particularly appropriate now that radiative corrections in the Standard Model are giving [3] indications on m_t . One should wonder whether these indications could be weakened or nullified by including supersymmetric diagrams. In particular, one could expect the conclusions on m_t , which are largely based on isospin violation, to be modified or diluted by the inclusion of diagrams involving the supersymmetric partners of the top quark, namely the stop squarks $\tilde{t}_{1,2}$.

In this paper we analyze the one-loop vacuum polarization radiative corrections involving stops, and include them in a global analysis of the available electroweak data. Whereas $\tilde{t}$ loop contributions could have been comparable to t -quark loop diagrams if typical squark masses were $< M_W$, the present lower limit [11] on $m_{\tilde{q}}$ weakens $\tilde{t}$ effects. We find that, if $m_{\tilde{q}} = 150$ GeV, including $\tilde{t}$ loops could decrease the central value of m_t by less than 5 GeV, whilst the upper limit on m_t could be decreased by at most 10 GeV. There is a negligible effect on the present lower bound on m_t .

We neglect the one-loop contributions coming from the gaugino/higgsino sector, which include box diagram and vertex corrections. The present lower limits on sparticle masses make these contributions rather small [7] compared with the corrections originated by smatter loops. On the other hand, all the smatter loops are considered, so

Radiative corrections now play a crucial rôle in the interpretation of electroweak data, such as precision measurements of the Z^0 peak at LEP [1]. As a first step, one calculates these radiative corrections in the Standard Model [2], and uses the data to constrain its unknown parameters, such as the top quark mass m_t and the Higgs boson mass M_H . At the moment, a global analysis of all the electroweak data favours $m_t > M_Z$ but is relatively insensitive to M_H [3], [4]. Such values of m_t are supported independently by the requirements of consistency between the measured values of M_Z and M_W , and of M_Z and deep-inelastic neutrino-nucleon scattering. On the other hand, within the framework of the Standard Model, neither the low-energy data nor measurements of M_Z and M_W allow very large values of m_t above about $2M_Z$.

There are many possible extensions of the Standard Model. Some of these, such as extra gauge bosons, could modify the interpretation of electroweak data already at the tree level, whilst many others could make important contributions to the radiative corrections. One of the best motivated of these latter extensions of the Standard Model is supersymmetry, and several calculations have been made of radiative corrections in supersymmetric models, [5], [6], [7], [8], [9], mainly directed to an estimate of the corrections to the ρ -parameter or to the weak boson masses. There are two classes of one-loop diagrams in the minimal supersymmetric extension of the Standard Model, namely those due to the gaugino/higgsino sector, and those due to chiral matter fields such as squarks and sleptons. A simultaneous analysis of all the supersymmetric contributions to the radiative corrections to the ρ -parameter, to the effective weak mixing angle

that together with stops and sbottoms, we include also the squark contributions coming from the partners of the two first generations. Their contribution is, however, much less important.

We consider simultaneously the supersymmetric one-loop corrections due to squark loops in all the relevant gauge boson self-energies, and their effects on the different quantities in terms of which the radiative corrections are parametrized, i.e. the ρ -parameter, the effective mixing angle appearing in the low-energy ν - q , ν - e and e - q interactions, defined [12] by $\sin^2 \vartheta_w(q^2) = \kappa(q^2) \sin^2 \vartheta_w$ with $\kappa(q^2) = 1 - \Delta(q^2)$, where q^2 is the squared momentum transfer characterizing the specific interaction, and the parameter Δr which contains the radiative contributions to the μ -decay rate not absorbed in G_F . In the definition of $\sin^2 \vartheta_w$ the so-called on-shell renormalization framework [13] is adopted, in which $\sin^2 \vartheta_w = 1 - M_W^2/M_Z^2$. The supersymmetric one-loop corrections are expressed in terms of the squark contributions to the self-energies by

$$\delta\rho|_{\text{self-energy}} = \frac{A_{WW}(0)}{M_W^2} - \frac{A_{ZZ}(0)}{M_Z^2}, \quad (1a)$$

$$\delta\Delta(s)|_{\text{self-energy}} = \frac{c_w}{s_w} \frac{A_{ZZ}(s)}{s} + \frac{c_w^2}{s_w^2} \text{Re} \left[\frac{A_{ZZ}(M_Z^2)}{M_Z^2} - \frac{A_{WW}(M_W^2)}{M_W^2} \right], \quad (1b)$$

$$\delta\Delta r|_{\text{self-energy}} = \frac{\text{Re} A_{WW}(M_W^2) - A_{WW}(0)}{M_W^2} - A'_{\gamma\gamma}(0) + \frac{c_w^2}{s_w^2} \text{Re} \left[\frac{A_{ZZ}(M_Z^2)}{M_Z^2} - \frac{A_{WW}(M_W^2)}{M_W^2} \right], \quad (1c)$$

where $s_w \equiv \sin \vartheta_w$, $c_w \equiv \cos \vartheta_w$, and the squark contributions to the different self-

energies appearing in eqs. (1) are given by

$$\frac{A_{WW}(0)}{M_W^2} \Big|_{\text{squarks}} = -\frac{3}{4} \frac{\alpha}{4\pi} \frac{1}{s_w^2} \frac{M_W^2}{M_W^2} \left\{ c_\theta^2 \tilde{C}(m_{\tilde{t}_1}, m_{\tilde{b}_L}) + s_\theta^2 \tilde{C}(m_{\tilde{t}_2}, m_{\tilde{b}_L}) + \tilde{C}(m_{\tilde{e}_L}, m_{\tilde{a}_L}) + \tilde{C}(m_{\tilde{a}_L}, m_{\tilde{d}_L}) \right\}, \quad (2a)$$

$$\frac{A_{ZZ}(0)}{M_Z^2} \Big|_{\text{squarks}} = -\frac{3}{4} \frac{\alpha}{4\pi} \frac{1}{s_w^2} \frac{8}{M_W^2} c_\theta^2 s_\theta^2 (c_R^i - c_L^i)^2 \tilde{C}(m_{\tilde{t}_1}, m_{\tilde{t}_2}), \quad (2b)$$

$$\frac{A_{WW}(M_Z^2)}{M_W^2} \Big|_{\text{squarks}} = -\frac{3}{4} \frac{\alpha}{4\pi} \frac{4}{s_w^2} \left\{ c_\theta^2 C(M_W^2, m_{\tilde{t}_1}, m_{\tilde{b}_L}) + s_\theta^2 C(M_W^2, m_{\tilde{t}_2}, m_{\tilde{b}_L}) + C(M_W^2, m_{\tilde{e}_L}, m_{\tilde{a}_L}) + C(M_W^2, m_{\tilde{a}_L}, m_{\tilde{d}_L}) \right\}, \quad (2c)$$

$$\frac{A_{ZZ}(M_Z^2)}{M_Z^2} \Big|_{\text{squarks}} = -\frac{3}{4} \frac{\alpha}{4\pi} \frac{8}{s_w^2 c_w^2} \left\{ (c_\theta^2 c_L^i + s_\theta^2 c_R^i)^2 C(M_Z^2, m_{\tilde{t}_1}, m_{\tilde{t}_2}) + (c_\theta^2 c_R^i + s_\theta^2 c_L^i)^2 C(M_Z^2, m_{\tilde{t}_2}, m_{\tilde{t}_1}) + 2c_\theta^2 s_\theta^2 (c_R^i - c_L^i)^2 C(M_Z^2, m_{\tilde{t}_1}, m_{\tilde{t}_2}) + \sum_{\tilde{q}=\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}} [(c_L^{\tilde{q}})^2 C(M_Z^2, m_{\tilde{q}_L}, m_{\tilde{q}_L}) + (c_R^{\tilde{q}})^2 C(M_Z^2, m_{\tilde{q}_R}, m_{\tilde{q}_R})] \right\}, \quad (2d)$$

$$\frac{A_{\gamma Z}(s)}{s} \Big|_{\text{squarks}} = -\frac{3}{4} \frac{\alpha}{4\pi} \frac{8}{s_w c_w} \left\{ Q_i [(c_\theta^2 c_L^i + s_\theta^2 c_R^i)^2 C(s, m_{\tilde{t}_1}, m_{\tilde{t}_2}) + (s_\theta^2 c_L^i + c_\theta^2 c_R^i)^2 C(s, m_{\tilde{t}_2}, m_{\tilde{t}_1})] + \sum_{\tilde{q}=\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}} Q_{\tilde{q}} [c_L^{\tilde{q}} C(s, m_{\tilde{q}_L}, m_{\tilde{q}_L}) + c_R^{\tilde{q}} C(s, m_{\tilde{q}_R}, m_{\tilde{q}_R})] \right\}, \quad (2e)$$

$$A'_{\gamma\gamma}(0) \Big|_{\text{squarks}} = \frac{\alpha}{4\pi} \sum_{\tilde{q}=\tilde{t}_1, \tilde{t}_2, \tilde{b}_L, \tilde{b}_R, \dots} Q_{\tilde{q}}^2 \left(\ln \frac{m_{\tilde{q}}^2}{\mu^2} + 1 \right). \quad (2f)$$

In the above formulae, $c_\theta \equiv \cos\theta$ and $s_\theta \equiv \sin\theta$, where θ is the mixing angle between the spartners of the t_L and t_R that is calculated by diagonalizing the mass-squared matrix

$$\begin{pmatrix} \tilde{t}_L & \tilde{t}_R \end{pmatrix}^* \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{LR}^2 & m_{RR}^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (3)$$

where

$$m_{LL}^2 = m_Q^2 + m_t^2 - \frac{1}{4}g_2^2(v_2^2 - v_1^2) + \frac{1}{12}g'^2(v_2^2 - v_1^2), \quad (4a)$$

$$m_{RR}^2 = m_{U_c}^2 + m_t^2 - \frac{1}{3}g'^2(v_2^2 - v_1^2), \quad (4b)$$

$$m_{LR}^2 = A_t m_t, \quad (4c)$$

with m_Q^2 and $m_{U_c}^2$ soft supersymmetry breaking mass terms that we assume for simplicity to be indistinguishable ($m_Q^2 = m_{U_c}^2 \equiv m_{\tilde{q}}^2$), and A_t another soft supersymmetry breaking parameter whose value can be estimated by model calculations [14]. The quantities $c_{R,L}^i$ are the Z^0 couplings of the $\tilde{t}_{R,L}$, namely

$$c_R^i = -\frac{2}{3}s_w^2, \quad c_R^b = \frac{1}{3}s_w^2, \quad (5a)$$

$$c_L^i = \frac{1}{2} - \frac{2}{3}s_w^2, \quad c_L^b = -\frac{1}{2} + \frac{1}{3}s_w^2. \quad (5b)$$

The mass-dependent factors $\tilde{C}(x, y)$ and $C(x, y, z)$ are defined as usual as

$$\tilde{C}(x, y) \equiv \frac{x^2 y^2}{x^2 - y^2} \ln \frac{x^2}{y^2} - \frac{1}{2}(x^2 + y^2), \quad (6a)$$

$$C(x, y, z) \equiv \frac{5}{18} - \frac{2}{3}\Sigma + \frac{1}{6}\delta^2 - \frac{1}{6}\ln \frac{y^2}{\mu^2} - \frac{1}{2}\delta(1 - \Sigma + \frac{1}{3}\delta^2) \ln \frac{y}{z} + \frac{1}{12}R^2 F(x, y, z), \quad (6b)$$

where μ^2 is the renormalization mass,

$$\Sigma = \frac{y^2 + z^2}{x}, \quad \delta = \frac{y^2 - z^2}{x}, \quad R^2 = 1 + \delta^2 - 2\Sigma,$$

and

$$F(x, y, z) = \sqrt{R^2} \ln \frac{1 - \sqrt{R^2} - \Sigma}{1 + \sqrt{R^2} - \Sigma} \quad \text{if } x < (y - z)^2,$$

or the appropriate analytical continuation. The first two generations of quarks make contributions analogous to those for $(\tilde{t}, \tilde{b})$, but with $m_{LR} \simeq 0$ and hence the corresponding angles of diagonalization $\theta \simeq 0$.

It is instructive to consider some special limiting cases of the above formulae. Consider first the limit where the average squark mass $m_{\tilde{q}} \rightarrow 0$. To simplify the expressions, we only keep the dominant contributions in powers of $\frac{m_t^2}{M_W^2}$. We find stop/sbottom contributions

$$\delta\rho|_{\text{self-energy}} \simeq \frac{3}{4} \frac{\alpha}{4\pi} \frac{1}{s_w^2} \frac{m_t^2}{M_W^2} \approx 0.0019 \frac{m_t^2}{M_W^2}, \quad (7a)$$

$$\delta\Delta(s)|_{\text{self-energy}} \simeq \delta\Delta r|_{\text{self-energy}} \simeq -\frac{c_w^2}{s_w^2} \delta\rho|_{\text{self-energy}} \approx -0.0063 \frac{m_t^2}{M_W^2}. \quad (7b)$$

In this small $m_{\tilde{q}}$ limit, the corresponding top-quark contributions are given by the same expressions. Thus, if this were the limit appropriate to the current electroweak data, the preferred value of m_t would be decreased by $1/\sqrt{2}$, putting it perilously close to the CDF lower limit [15] on m_t . However, UA2 and CDF both establish lower bounds on $m_{\tilde{q}}$ of about 70 to 80 GeV [11], and present CDF data are sensitive to $m_{\tilde{q}} \leq 120$ GeV at least. In the limit where $m_{\tilde{q}} \gg m_t$, the stop and sbottom contributions would be (again to leading order in $\frac{m_t^2}{M_W^2}$, assuming for simplicity equal Higgs v.e.v's, and writing $a = \frac{A_t}{2m_{\tilde{q}}}$):

$$\delta\rho|_{\text{self-energy}} \simeq \frac{1}{4} \frac{\alpha}{4\pi} \frac{1}{s_w^2} \frac{m_t^2}{M_W^2} \frac{m_t^2}{m_{\tilde{q}}^2} (1 - 2a^2 + \frac{2}{3}a^4) \approx 0.0006 \frac{m_t^2}{M_W^2} \frac{m_t^2}{m_{\tilde{q}}^2}, \quad (8a)$$

$$\delta\Delta(s)|_{\text{self-energy}} \simeq \delta\Delta r|_{\text{self-energy}} \simeq -\frac{1}{4} \frac{\alpha}{4\pi} \frac{1}{s_w^4} \frac{m_t^2}{M_W^2} \frac{m_t^2}{m_{\tilde{q}}^2} \approx -0.0059 \frac{m_t^2}{M_W^2} \frac{m_t^2}{m_{\tilde{q}}^2}, \quad (8b)$$

(taking $\alpha = 1$ in (Sa)) giving much less sensitivity to m_t . If $m_{\tilde{q}}$ is close to the UA2/CDF lower limits [11], the truth is somewhere between (7) and (8) as we shall now see.

As in previous global analyses of electroweak data [3], we determine the preferred values of $\sin^2\theta_w$ as functions of m_t incorporating one-loop radiative corrections separately in each of the 4 sectors: $\nu - q$, $\nu - e$, $e - q$ and Vector Boson Masses (VBM). We have explored the m_t -dependence of the preferred values of $\sin^2\theta_w$ for representative choices of supersymmetric model parameters $m_{\tilde{q}}$ and $\tan\beta$. For each value of $m_{\tilde{q}}$ we take from ref. [14] a parametrization of the trilinear soft supersymmetry-breaking parameter $A_t \simeq 1.6m_{\tilde{q}}$ to determine the amount of stop squark ($\tilde{t}_L, \tilde{t}_R$) mixing. LEP lower bounds on the mass of the lightest neutral scalar Higgs boson [16] impose the constraint $\tan\beta \geq 1.3$, and we find that the effects on m_t of the supersymmetric radiative corrections are not greatly changed if $\tan\beta$ is increased.

Fig. 1 shows our results for the choice $m_{\tilde{q}} = 150$ GeV and $\tan\beta = 1.3$. We see that the preferred values of $\sin^2\theta_w$ in the different sectors diverge more rapidly than in the minimal Standard Model as m_t is increased. These are not noticeable effects for $m_t \leq 100$ GeV, but for heavier m_t the $\nu - q$ value of $\sin^2\theta_w$ is increased, and the values for the $\nu - e$, $e - q$ and VBM sectors decreased, relative to those in the Standard Model. Since the purpose of this paper is to study the change in previous results when $\tilde{q}$ loops are included, we do not give here a general discussion of errors and uncertainties in the global analysis, which are discussed extensively elsewhere. In particular we simply fix $m_c = 1.45$ GeV as in [3]. As discussed in [3], the effect of inflating the error in the $\nu - q$ value of $\sin^2\theta_w$, which corresponds roughly to treating m_c as a free parameter, would be to change the central value of m_t by about 8 GeV.

Combining all the sectors, we find (here and in the following the Higgs mass is taken fixed and equal to the Z^0 mass)

$$m_t = 131^{+24}_{-28} \text{ GeV} \quad , \quad (9)$$

and

$$\sin^2\theta_w = 0.2272^{+0.0035}_{-0.0032} \quad , \quad (10)$$

for $m_{\tilde{q}} = 150$ GeV and $\tan\beta = 1.3$, to be compared with the latest Standard Model values [4]

$$m_t = 135^{+27}_{-31} \text{ GeV} \quad , \quad (11)$$

and

$$\sin^2\theta_w = 0.2271^{+0.0035}_{-0.0032} \quad . \quad (12)$$

Thus the central value of m_t is reduced by about 4 GeV and the one-standard deviation upper limit is decreased by about 7 GeV relative to the Standard Model values (see eqs. (9) and (11)).

As could be expected, larger values of $m_{\tilde{q}}$ give smaller shifts in m_t , as shown and in Figs. 2 and 3. The former shows the χ^2 distributions as functions of m_t for different values of $m_{\tilde{q}}$. We note that the minimum value of χ^2 is essentially independent of $m_{\tilde{q}}$, as is the best fit value of $\sin^2\theta_w$ (see eqs. (10) and (12)).

Fig. 3 shows the one-standard-deviation range of m_t for different values of $m_{\tilde{q}} \geq 80$ GeV, which is the present experimental lower limit published by the UA2 and CDF Collaborations [11]. We see that the one-standard-deviation upper bound on m_t can

be significantly decreased, to 143 GeV for $m_{\tilde{t}} = 80$ GeV. On the other hand, the one-standard-deviation lower bound on m_t is almost independent of $m_{\tilde{t}}$.

Table. Values of m_t for various choices of $m_{\tilde{t}}$ and $\tan\beta$. All the masses in GeV.

$\tan\beta$	$m_{\tilde{t}} = 100$	$m_{\tilde{t}} = 150$	$m_{\tilde{t}} = 200$
1.3	+21 127 -26	+24 131 -28	+24 133 -30
1.5	+21 127 -26	+24 131 -29	+25 133 -30
2	+22 127 -27	+25 131 -29	+24 133 -30
4	+23 126 -30	+25 131 -30	+26 132 -30
8	+24 124 -31	+25 130 -31	+26 132 -31

We have also explored the effect of increasing $\tan\beta$. As seen in the Table, the central value of m_t decreases slightly, whilst the error increases, so that the one-standard-deviation upper limit is essentially unchanged. We have also calculated results for different values of M_H [4]. Varying M_H between 25 GeV and 1 TeV within the Standard Model, we find effects on the central value of m_t of -7 GeV and $+17$ GeV, respectively. This variation with M_H shows that the squark, and in particular stop, radiative cor-

rection effects are at most comparable with those of the Higgs sector in the Standard Model.

Our results indicate that the radiative correction estimate of m_t made in refs. [3], [4] is remarkably stable with respect to the introduction of new physics. Although the effects of stops could in principle have been as large as those of tops, in practice, since we already know that $m_{\tilde{t}} \geq M_W$, the stop effects are considerably smaller. Indeed, we find that they are at most comparable with the effect of the Higgs boson in the Standard Model, and considerably smaller than the current errors of ± 30 GeV on m_t . If anything, the effect of including stop loops would be to decrease the preferred value of m_t by at most 10 GeV.

In the future, precision electroweak measurements will be dominated by precision data from LEP and other high-energy accelerators at $Q^2 \geq 10^4$ GeV². The inclusion of supersymmetric radiative corrections in the analysis of these data is likely to be essential if sparticle masses are ≤ 1 TeV as we expect. In particular, if one looks beyond the current attempt to predict m_t to the time when one attempts to determine the parameters of the Higgs sector via radiative corrections, it is clear that the possibility of supersymmetry will have to be taken into account.

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Figure Captions

Fig. 1 – The dependence on m_t of the central values of $\sin^2\vartheta_w$ extracted from the different electroweak sectors: $\nu-q$, $\nu-e$, $e-q$ and the vector boson masses (VBM). Also shown are the central value and the one-standard-deviation range of $\sin^2\vartheta_w$ extracted from M_W/M_Z , which is independent of m_t . The solid lines are calculated in the minimal Standard Model, whilst the dashed lines are calculated including squark loops assuming $m_{\tilde{q}} = 150$ GeV and $\tan\beta = 1.3$. In this and subsequent figures we have assumed $m_c = 1.45$ GeV when fitting the $\nu-q$ sector and $M_H = M_Z$.

Fig. 2 – The χ^2 distributions as functions of m_t for global fits to the electroweak data assuming different values of $m_{\tilde{q}}$ as indicated.

Fig. 3 – The dependence of the central value and one-standard-deviation range of m_t on $m_{\tilde{q}}$, as extracted from global fits. In the upper part of the figure the corresponding limit for $m_{\tilde{q}} \rightarrow \infty$, i. e. the Standard Model result, is indicated.

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