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Corrections to b , t quark masses and τ lepton mass in SUGRA including CP phases

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Abstract

A brief review is given of recent analyses of the effects of CP phases on the supersymmetric QCD and supersymmetric electroweak contributions to the b and t quark masses and to the τ lepton mass in SUGRA models. The effects of CP phases on the supersymmetric contributions are found to be significantly large for the b quark mass as they can change both its sign and its magnitude. Thus with the inclusion of CP phases the supersymmetric correction to the b quark mass can be as much as fifty percent or more of the total b quark mass. For the case of the τ lepton, the effects of CP phases on the supersymmetric correction is also relatively large as it can again affect both the sign and the magnitude of the τ mass correction. However, in this case the overall correction is found to be only a few percent. The effect of CP phases on SUSY contribution to the t quark mass was also investigated. However, in this case the overall correction is less than a percent with or without the inclusion of phases. These results have important implications for $b - \tau$ unification and for $b - t - \tau$ unification in the context of unified theories.

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1 Introduction

Supersymmetric corrections to the b , t quark masses and to the τ lepton mass are of great importance. These corrections affect importantly analyses of $b - \tau$ and $b - t - \tau$ couplings in unified models of particle interactions[1, 2]. Further, such corrections can also affect a variety of low energy phenomena such as decays of the Higgs into $b\bar{b}$, $\tau\bar{\tau}$, $c\bar{c}$ etc which are potentials sources as signals of supersymmetry. In this talk we discuss the effect of CP phases on supersymmetric corrections to the b , t quark masses and to the τ lepton mass. Previous analyses have not fully taken account of the phases[3, 4, 5, 6, 7] For the b and t quark masses these arise from the SUSY QCD and SUSY electroweak contributions from the exchange of the gluino, charginos and neutralinos. For the τ lepton mass they arise from the SUSY electroweak contributions from the exchange of the charginos and the neutralinos. The CP phases in SUSY have a long history. It was realized early on that the SUSY CP phases could pose a severe problem in that they could generate large contributions to the electric dipole moments of the neutron and of the electron which may exceed the experimental limits[8, 9]. Additionally one now also has very stringent limits on the atomic edms specifically on the edm of Hg ¹⁹⁹ (see Ref.[10]). Initially the technique followed was to suppress the edm contributions by simply adjusting the CP phases to be small[11]. However, since then other ways have been devised which allow one to suppress the edms while allowing for large phases[12, 13, 14, 15, 16, 17, 18]. One technique of interest here is the cancellation mechanism[14] wherein the edm contributions are suppressed by cancellations among various contributions. With this mechanism one can allow for large phases consistent with the current edm constraints. The process of cancellation is facilitated by the presence of several phases. Thus the minimal supergravity model (mSUGRA)[19] can allow for two phases so that the parameter space including phases is described by m_0 , $m_{\frac{1}{2}}$, $|A_0|$, $\tan\beta$, α_{A_0} and θ_μ , where m_0 is the universal scalar mass, $m_{\frac{1}{2}}$ is the universal gaugino mass, $|A_0|$ is the universal trilinear coupling, $\tan\beta = H_2/H_1$ where H_2 gives mass to the up quark and H_1 gives mass to the down quark and the lepton, α_{A_0} is the phase of A_0 and θ_μ is the phase of the Higgs mixing parameter μ . However, in the presence of nonuniversalities the more general SUGRA model can accommodate more phases. Thus, for example, due to a non flat gauge kinetic energy function one may have the $SU(3)_C \times SU(2)_L \times U(1)$ gaugino masses which are

nonuniversal so that $\tilde{m}_i = |\tilde{m}_i|e^{i\xi_i}$ ($i = 1, 2, 3$) In this case one has a greater parameter space for the cancellation mechanism to operate. The presence of phases has typically a large effect on low energy phenomenology and a small sample of these is given in Refs. [20, 21, 22, 23, 24, 25, 26, 27, 28] while a sample of some more recent works are given in Ref.[29] A more complete list of works can be seen in Ref. [30].

We discuss now some details of the technique for the computation of the SUSY mass correction to the quark and lepton masses. We follow closely the analysis of Ref.[31]. We begin by noting that the pole mass M_b which is the physical mass of the b quark is related to the running mass $m_b(M_b)$ as follows

$$M_b = \left(1 + \frac{4\alpha_3(M_b)}{3\pi} + 12.4 \frac{\alpha_3(M_b)^2}{\pi^2}\right) m_b(M_b) \quad (1)$$

where the corrections in the brace on the right hand side are the QCD corrections up to two loop level[1]. The quantity $m_b(M_b)$ is obtained from $m_b(M_Z)$ by use of renormalization group evolution. In the analysis here we will focus on the computation of $m_b(M_Z)$ which is the running b quark mass at the Z scale. This quantity can be written in the form

$$m_b(M_Z) = h_b(M_Z) \frac{v}{\sqrt{2}} \cos \beta (1 + \Delta_b) \quad (2)$$

where Δ_b is loop correction to m_b [3, 4, 5, 7]. We give now further details of our analysis. Our procedure is similar to that of Ref[7]. We begin by noting that at the tree level one has a coupling of the b quark only to H_1^0 . At the loop level the coupling of H_1^0 is modified and there is in addition a correction to the couplings from H_2^0 . Thus in the presence of loop corrections one can write the b quark couplings as follows[7]

$$-L_{bbH^0} = (h_b + \delta h_b) \bar{b}_R b_L H_1^0 + \Delta h_b \bar{b}_R b_L H_2^0 + H.c. \quad (3)$$

Eq. (3) is the effective coupling of the b quark to the Higgs which can be used to compute the loop correction to b quark mass. One finds

$$\Delta_b = \left[\frac{Re(\Delta h_b)}{h_b} \tan \beta + \frac{Re \delta h_b}{h_b} \right] \quad (4)$$

Because of the presence of phases the loop corrections Δh_b and δh_b will in general be complex and the effective mass term for the b quark will have the form

$$-L_b = (m_b^0 + \Delta_1) \bar{b} b + i \Delta_2 \bar{b} \gamma_s b \quad (5)$$

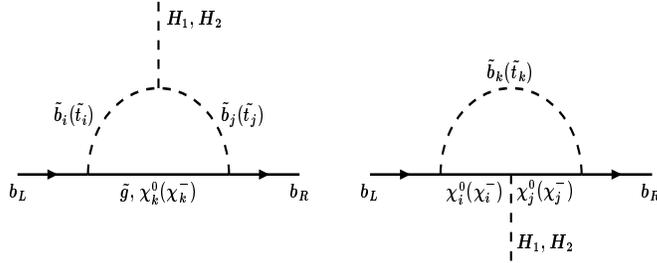


Figure 1: One loop SUSY QCD and SUSY electroweak contribution to the b quark mass arising from exchange of gluino, charginos and neutralinos in the loop.

where $\gamma_5^\dagger = \gamma_5$ and $\Delta_{1,2}$ are real. In Eq. (5) the $i\gamma_5$ term can be removed by the transformation $b = e^{i\frac{\theta}{2}\gamma_5}b'$ with an appropriate choice of θ . In the terms of the redefined fields one has

$$-L_b = m_b \bar{b}'b', \quad m_b = m_b^0 + \Delta_1 + \frac{1}{2} \frac{\Delta_2^2}{m_b^0} + .. \quad (6)$$

Eq. (6) shows that the Δ_2 term is essentially a higher order correction and can be safely ignored at the one loop level. Similar considerations hold in the computation of loop corrections to the τ lepton mass and to the t quark mass.

2 CP Phase dependent loop corrections to the b , t quark masses and τ lepton mass

We begin with a discussion of correction to the b quark mass. Loop contributions to the b quark mass arise from the exchange of the gluino, chargino and neutralinos (see Fig. 1)

$$\Delta_b = \Delta_b^{\tilde{g}} + \Delta_b^{\tilde{\chi}^+} + \Delta_b^{\tilde{\chi}^0} \quad (7)$$

Here $\Delta_b^{\tilde{g}}$ is the gluino exchange contribution, $\Delta_b^{\tilde{\chi}^+}$ is the chargino exchange contribution, and $\Delta_b^{\tilde{\chi}^0}$ is the neutralino exchange contribution. The full expressions for all these three contributions can be found in Ref. [31]. We will discuss here for illustrative purposes the gluino exchange contribution explicitly. The total correction to the b quark mass from

gluino exchange including the effects of CP phases is given by[31]

$$\begin{aligned}\Delta_b^{\tilde{g}} = & -\frac{2\alpha_s}{3\pi}m_{\tilde{g}}\tan\beta\sum_{i=1,2}\sum_{j=1,2}Re(\mu^*e^{-i\xi_3})|D_{b1i}^*D_{b2j}|^2f(m_{\tilde{g}}^2,m_{b_i}^2,m_{b_j}^2) \\ & +\frac{2\alpha_s}{3\pi}m_{\tilde{g}}\sum_{i=1}^2\sum_{j=1}^2|D_{b2j}|^2|D_{b1j}|^2Re(m_0A_b e^{-i\xi_3})f(m_{\tilde{g}}^2,m_{b_i}^2,m_{b_j}^2)\end{aligned}\quad (8)$$

where D is defined so that $\tilde{b}_L = \sum_{i=1}^2 D_{b1i}\tilde{b}_i$ and $\tilde{b}_R = \sum_{i=1}^2 D_{b2i}\tilde{b}_i$ where \tilde{b}_i are the b squark mass eigen states and f is defined by

$$f(a,b,c) = \frac{abl\ln(a/b) + bcl\ln(b/c) + acl\ln(c/a)}{(a-b)(b-c)(a-c)}\quad (9)$$

This result is valid for arbitrary values of $\tan\beta$. To compare our result to previous analyses we set the phases to zero and take the large $\tan\beta$ limit. In this limit we find

$$\Delta_b^{\tilde{g}} = \frac{2\alpha_3\mu M_{\tilde{g}}}{3\pi}\tan\beta f(m_{b_1}^2,m_{b_2}^2,M_{\tilde{g}}^2)\quad (10)$$

The above result is exactly what is obtained in previous analyses in the limit of no phases and large $\tan\beta$ [3, 4]. Similarly the chargino exchange contribution in the limit when $\tan\beta$ is large and the phases are set to zero gives[31]

$$\Delta_b^{\tilde{\chi}^+} = \frac{Y_t\mu m_0 A_t}{4\pi}\tan\beta f(m_{t_1}^2,m_{t_2}^2,\mu^2)\quad (11)$$

where $Y_t = h_t^2/4\pi$. Again the above result agrees with the result of previous analyses without phases valid for large $\tan\beta$ [3, 4]. One notices that both the limiting forms of the gluino and the chargino exchange contributions depend linearly on $\tan\beta$. Because of this the loop corrections to the b quark mass can become large for large $\tan\beta$. A very similar result holds for the case of the τ lepton except that here one only has chargino and neutralino exchange contributions as exhibited in Fig. (2). For the top quark the SUSY QCD and SUSY electroweak corrections have a very different dependence on $\tan\beta$. Thus the top mass at the Z scale is given by

$$m_t(M_Z) = \lambda_t(M_Z)\frac{v}{\sqrt{2}}\sin\beta(1 + \Delta_t)\quad (12)$$

where Δ_t gives the loop correction to m_t which arise from the loop corrections involving the gluino, chargino and neutralino exchange contributions. The effective ttH^0 interaction in this case is given by

$$-L_{ttH^0} = (h_t + \delta h_t)\bar{t}_R t_L H_2^0 + \Delta h_t \bar{t}_R t_L H_1^0 + H.c.\quad (13)$$

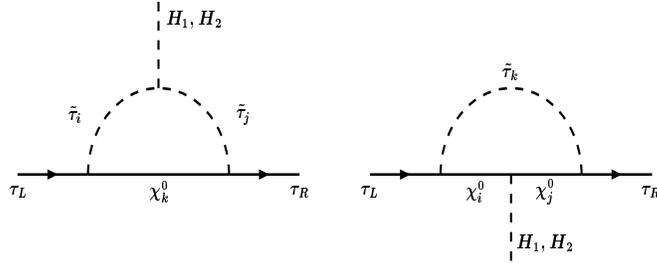


Figure 2: One loop SUSY electroweak correction to the τ lepton mass arising from the exchange of charginos in the loop.

where

$$\Delta_t = \left(\frac{\text{Re}(\Delta h_t)}{h_t} \cot\beta + \frac{\text{Re}(\delta h_t)}{h_t} \right) \quad (14)$$

The computation for Δ_t in the presence of CP phases is given in Ref.[31]. Here we observe that unlike the b quark case the first term in Eq. (14) is suppressed because of $\cot\beta$ factor rather than enhanced when $\tan\beta$ gets large. Consequently the size of SUSY loop correction to the t quark mass is much smaller than for the case of the b quark mass.

Table 1. Electron, neutron and H_g edms (From Ref.[31])

case	$m_0, m_{\frac{1}{2}}, A_0 $	$\alpha_A, \xi_1, \xi_2, \xi_3$
(a)	200, 200, 4	1, .5, .659, .633
(b)	370, 370, 4	2, .6, .653, .672
(c)	320, 320, 3	.8, .4, .668, .6
$d_e(ecm)$	$d_n(ecm)$	$C_{H_g}(cm)$
(a) 1.45×10^{-27}	9.2×10^{-27}	7.2×10^{-27}
(b) -1.14×10^{-27}	-7.9×10^{-27}	2.87×10^{-26}
(c) -3.5×10^{-27}	7.1×10^{-27}	2.9×10^{-26}

Table Caption: $\theta_\mu = 2.5$ rad for cases (a), (b), (c) in the table.

3 Discussion of results

In the numerical analysis we will assume SUGRA models with nonuniversalities consistent with the FCNC constraints. Specifically, we assume that the parameter space of the model is defined by the parameters m_0 , $m_{\frac{1}{2}}$, A_0 , $\tan \beta$, θ_μ and ξ_i ($i=1,2,3$). We begin by discussing the satisfaction of the edm constraints which are already rather stringent. Thus for the electron the current experimental limit on the edm is $d_e < 4.3 \times 10^{-27} ecm$ [9] while for the neutron it is $d_n < 6.5 \times 10^{-26} ecm$ [8]. As noted earlier the atomic edm constraints are also now very stringent. Thus for Hg^{199} atom one has $d_{Hg} < 9 \times 10^{-28} ecm$ [10]. This EDM constraint could be translated into a constraint on a specific combination of the chromo electric dipole moments of u, d and s quarks so that $C_{Hg} = |d_d^C - d_u^C - 0.012d_s^C|$ is constrained to satisfy $C_{Hg} < 3.0 \times 10^{-26} cm$. In Table 1 we present cases where in SUGRA models with nonuniversalities you have satisfaction of the edm constraints for the electron, for the neutron and for the Hg^{199} edm. The three cases in Table 1 all have large phases typically order unity and still one has satisfaction of the edm constraints. We discuss now the effect of these large phases on the analysis of supersymmetric contributions to the b quark. In Fig. 3 we give an analysis of the SUSY contribution to the b quark mass as a function of $\tan \beta$ where the other parameters correspond to the three cases given in Table 1. The lower curves are with phases while the upper curves are without phases. Fig. 3 exhibits several interesting features. First, one finds that the SUSY correction as expected does indeed increase essentially linearly with $\tan \beta$ for large $\tan \beta$. Further, one finds that the effects of phases for each of the three cases is rather drastic in that the sign as well as the magnitude of the supersymmetric correction is affected. We also note that with the inclusion of the susy correction the effect can be as much as 50% or more. This is a rather large correction showing the importance of the supersymmetric correction as well as of the phases. A similar analysis but for the τ lepton mass is given in Fig. 4. Here also one finds as expected an essentially linear dependence on $\tan \beta$ for large $\tan \beta$. Further, one also finds that the phases affect both the sign as well as the magnitude of the correction to the τ lepton mass. However, in this case one finds that the overall correction is typically order a few percent. This smaller relative correction is due essentially to the fact that in this case one does not have a SUSY QCD correction but only only a SUSY electroweak correction to the τ lepton mass. In Fig. 5 we give an analysis of the SUSY

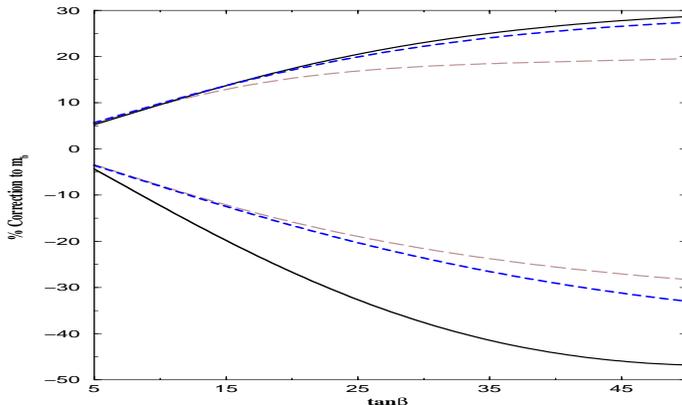


Figure 3: Exhibition of the b quark mass correction $\Delta m_b/m_b$ in percentage as a function of $\tan \beta$ with the other parameters given by the three cases (a), (b) and (c) of Table 1. In the lower half plane, the long dashed curve corresponds to the case (a), the solid curve corresponds to the case (b) and the dashed curve corresponds to the case (c). We note that in each of the cases (a), (b) and (c) the edm constraints for the electron, the neutron and Hg^{199} are satisfied for the case $\tan \beta = 50$. Similar upper curves have all the same parameters as the lower ones except that the phases are all set to zero. The figures is taken from Ref.[31]

QCD and SUSY electroweak correction to the t quark mass. In this case there is no $\tan \beta$ enhancement of the SUSY mass correction. Thus although the CP phases still have a very significant effect of the SUSY mass correction, the entire correction in this case is typically less than a percent or so.

4 Conclusion

In this talk we have given a brief overview of the supersymmetric corrections to the b and t quark masses and to the τ lepton mass including the effects of CP phases which have been ignored in previous analyses. It is found that the effects of these phases on the susy correction to the b quark mass can be large enough to change both the sign and the magnitude of the correction. Including the effects of the CP phases the supersymmetric correction can be as much as fifty percent or more of the total mass of the b quark mass.

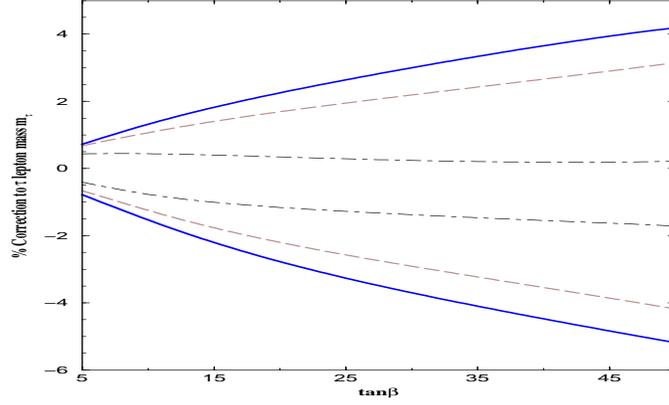


Figure 4: Same as Fig. (3) except that the plot is for the τ lepton mass correction $\Delta m_\tau/m_\tau$ in percentage as a function of $\tan\beta$ for the three cases (a), (b) and (c) of Table 1. The figures is taken from Ref.[31]

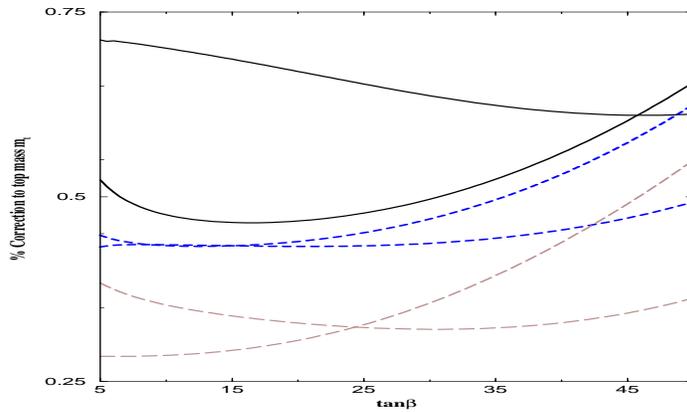


Figure 5: Same as Fig. (3) except that the plot is for the t quark mass correction $\Delta m_t/m_t$ in percentage as a function of $\tan\beta$ for the three cases (a), (b) and (c) of Table 1. The figures is taken from Ref.[31]

For the case of the τ lepton the supersymmetric correction, as in the case of the b quark, is proportional to $\tan\beta$ for large $\tan\beta$ and further, it can change both the sign and the magnitude when one includes the phases. However, in this case the overall correction including the phases is typically much smaller than in the case of the b quark mass, i.e., only of the order of a few percent. The smaller correction is in part due to the fact that in this case the correction is only electroweak. Similarly, the supersymmetric correction to the top quark mass is found to be very sensitive to the phases. In this case the correction does not have a large enhancement factor for large $\tan\beta$. Thus, overall the correction is typically less than a percent. As pointed out in Sec.1 the supersymmetric corrections to quark and lepton masses plays an important role in $b-t$ and $b-t-\tau$ unification in the context of grand unified theory. Thus the phases have important implications in such analyses. In addition to affecting corrections to the quark and lepton masses, the CP phases also affect the Higgs vertices involving couplings of the Higgs to the quarks and the leptons. These modifications lead to important CP effects on the decay of the Higgs to $b\bar{b}$, $\tau\bar{\tau}$ and $c\bar{c}$ [32]. Thus accurate measurement of the branching ratios of the Higgs to $b\bar{b}$, $\tau\bar{\tau}$ and $c\bar{c}$ in future collider experiments can reveal the presence of supersymmetry and of CP phases.

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