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Precise predictions for m_t, V_{cb}, and $\tan\beta$

Greg W. Anderson and Stuart Raby*
Department of Physics, The Ohio State University, Columbus, Ohio 43210
Savas Dimopoulos
Department of Physics, Stanford University, Stanford, California 94305
Lawrence J. Hall
Physics Department and Lawrence Berkeley Laboratory, University of California, Berkeley, Berkeley, California 94720
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The fermion mass and mixing angle predictions of a recently proposed framework are investigated for large b and τ Yukawa couplings. A new allowed region of parameters is found for this large $\tan\beta$ case. The two predictions that are substantially altered, m_t and $\tan\beta$, are displayed, including the dependence on the input $|V_{cb}|$, m_c, m_b, and α_s. A simple restriction on this framework yields an additional prediction for $|V_{cb}|$. If the b, t, and τ Yukawa couplings are equal at the GUT scale then $|V_{cb}|$ is predicted and the top quark mass is constrained to lie in the range $m_t=179\pm4$ GeV.

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I. INTRODUCTION

The majority of the parameters of the standard model, thirteen out of eighteen, originate in the mass matrices of the quarks and charged leptons. The most promising idea which has led to predictions of some of these flavor parameters is the reduction of parameters made possible by a combination of grand unified symmetries [1] and flavor symmetries [2]. The most successful prediction of any parameter of the standard model is that of the weak mixing angle in supersymmetric grand unified theories (GUT's) [3]: the predicted value of 0.233±0.002 (where the error represents an estimate of higher order corrections and thresholds uncertainties) should be compared with the experimental value of 0.233±0.001. The first flavor parameter to be predicted in GUT's was m_b/m_τ [4]. This prediction is affected by the mass of the heavy top quark and again favors supersymmetric unification [5,10].

Recently three of us made the most predictive analysis of fermion masses and mixing angles yet [6], based on the family symmetries of Georgi and Jarlskog [7] and on supersymmetric GUT's. Including $\tan\beta$, the ratio of electroweak VEV's, there are fourteen flavor parameters, and these are given in terms of only eight GUT parameters, yielding six predictions. To obtain these predictions the Yukawa matrices must be scaled with the renormalization group (RG) from GUT to weak scales. Previously this was done by including the one-loop RG scaling effects induced by gauge and top quark Yukawa interactions [6,8]. This is sufficient only for moderate values of $\tan\beta$, since as $\tan\beta$ is increased, the b and τ Yukawa couplings increase and contribute to the RG scaling.

In this paper we reanalyze this framework [6] using the full one-loop RG equations, thus including RG scaling effects induced by the b and τ Yukawa couplings. There are several reasons for doing this. Previous analyses [6,8] showed that $\tan\beta$ cannot be less than about 2 when the strong coupling constant is $\alpha_s(m_z)=0.109$. Furthermore, as $\tan\beta$ is increased so V_{cb} is decreased, improving the agreement with experiment. It is clearly of great interest to know whether this agreement can be further improved by going to values of $\tan\beta$ outside the range of validity of previous calculations. Furthermore, the previous predictions for m_t will be affected by large b and τ Yukawa couplings, which contribute to the RG equation (RGE) for the t Yukawa coupling. Finally, studying the case of large b and τ Yukawa couplings allows an additional reduction in the number of parameters, namely, that the GUT scale b and t Yukawa couplings are equal.

II. EVOLVING THE GUT SCALE TEXTURE

The *Ansätze* for the three Yukawa matrices at the renormalization group scale $\mu=M_G$ is

$$\mathbf{U}=\begin{bmatrix}0 & C & 0\\ C & 0 & B\\ 0 & B & A\end{bmatrix},\quad \mathbf{D}=\begin{bmatrix}0 & Fe^{i\phi} & 0\\ Fe^{-i\phi} & E & 0\\ 0 & 0 & D\end{bmatrix},\quad \mathbf{E}=\begin{bmatrix}0 & F & 0\\ F & -3E & 0\\ 0 & 0 & D\end{bmatrix}.$$

Below the GUT scale, the symmetries which maintained zero entries and preserved the relationship between $\mathbf{D}$ and $\mathbf{E}$ are broken. The evolution of the Yukawa matrices between the GUT scale and the weak scale is given by [9]

$$\mu\frac{d}{d\mu}\mathbf{U}=\frac{1}{(4\pi)^2}\{[3\,\mathrm{Tr}(\mathbf{U}\mathbf{U}^\dagger)-(\tfrac{16}{3}g_c^2+3g^2+\tfrac{13}{9}g'^2)]\mathbf{U}+3\mathbf{U}\mathbf{U}^\dagger\mathbf{U}+\mathbf{D}\mathbf{D}^\dagger\mathbf{U}\}\,, \quad (2.1a)$$

$$\mu\frac{d}{d\mu}\mathbf{D}=\frac{1}{(4\pi)^2}\{[\mathrm{Tr}(\mathbf{E}\mathbf{E}^\dagger+3\mathbf{D}\mathbf{D}^\dagger)-(\tfrac{16}{3}g_c^2+3g^2+\tfrac{7}{9}g'^2)]\times\mathbf{D}+3\mathbf{D}\mathbf{D}^\dagger\mathbf{D}+\mathbf{U}\mathbf{U}^\dagger\mathbf{D}\}\,, \quad (2.1b)$$

*On leave of absence from Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

$$\mu\frac{d}{d\mu}\mathbf{E}=\frac{1}{(4\pi)^2}\{[\mathrm{Tr}(\mathbf{E}\mathbf{E}^\dagger+3\mathbf{D}\mathbf{D}^\dagger)-(3g^2+3g'^2)]\mathbf{E}+3\mathbf{E}\mathbf{E}^\dagger\mathbf{E}\}\ . \quad (2.1c)$$

In general, **U** and **D** are neither symmetric nor Hermitian below the GUT scale. We stop the RGE evolution at a scale $\mu\simeq m_t$. The weak scale quark and lepton mass matrices are then given by

$$m_U=\mathbf{U}\frac{v\sin\beta}{\sqrt{2}},\quad m_D=\mathbf{D}\frac{v\cos\beta}{\sqrt{2}},\quad m_E=\mathbf{E}\frac{v\cos\beta}{\sqrt{2}}\ , \quad (2.2)$$

where $v=246$ GeV. These three weak scale Yukawa matrices are diagonalized by the unitary matrices V_u^L, V_u^R, V_d^L, V_d^R, and V_e defined by $\mathbf{U}^{\rm diag}=V_u^L\mathbf{U}V_u^{R\dagger}$, $\mathbf{D}^{\rm diag}=V_d^L\mathbf{D}V_d^{R\dagger}$, and $\mathbf{E}^{\rm diag}=V_e\mathbf{E}V_e^\dagger$. The Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix is then given by $V_{\rm CKM}=V_u^LV_d^{L\dagger}$. Below the weak scale we evolve the fermion masses to one loop in QED and two loops in QCD. We define the resulting mass enhancement factors by $\eta_f=m_f(m_f)/m_f(m_t)$ for $f=e,\mu,\tau,c,b$ and $\eta_f=m_f(1\ \mathrm{GeV})/m_f(m_t)$ for $f=u,d,s$. The dependence of these mass enhancement factors on the strong coupling constant, shown in Fig. 1, has important consequences.

All of the numerical results quoted in this paper are a result of running and diagonalizing the Yukawa couplings in matrix form according to the full one-loop RGE. The eight parameters A, B, C, D, E, F, ϕ, and $\tan\beta$ are best determined from the masses and mixing angles: m_e, m_μ, m_τ, m_c, m_b, m_u/m_d, $|V_{us}|$, and $|V_{cb}|$. Consider a fixed but arbitrary value of $\tan\beta$. Since the RG evolution of the Yukawa matrix elements can be significantly affected by all three third generation Yukawa couplings, the parameters A and D must be determined first. Both of these couplings can be reliably determined by the combined constraints of the τ lepton mass and the b/τ ratio. Since the charged lepton masses are well known and the RGE for lepton masses is not complicated by uncertainties in α_s, the couplings E and F are then very reliably determined by the electron and muon masses. The parameter B can then be fixed by the charm quark mass, C set by the up to down ratio, and the phase ϕ determined from $|V_{us}|$. Finally two solutions for $\tan\beta$ can be found as a function of $|V_{cb}|$. This is a consequence of the relation $|V_{cb}|=\sqrt{m_c/m_t}$.[1] The smaller branch corresponds to the solution obtained previously [6], while the larger branch represents a new solution (see Fig. 2). Once $\tan\beta$ is determined we have a prediction for m_t and the remaining fermion masses and mixing angles

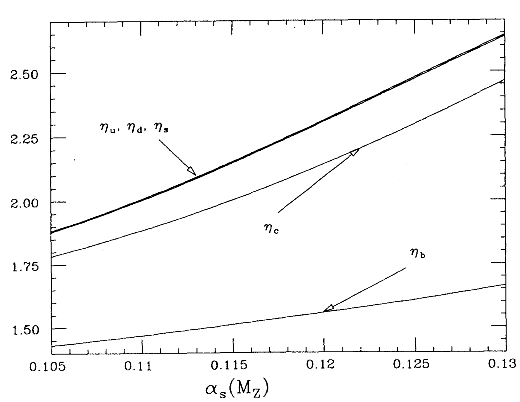

FIG. 1. A plot of the RGE mass enhancement factors η_f vs $\alpha_s(m_Z)$.

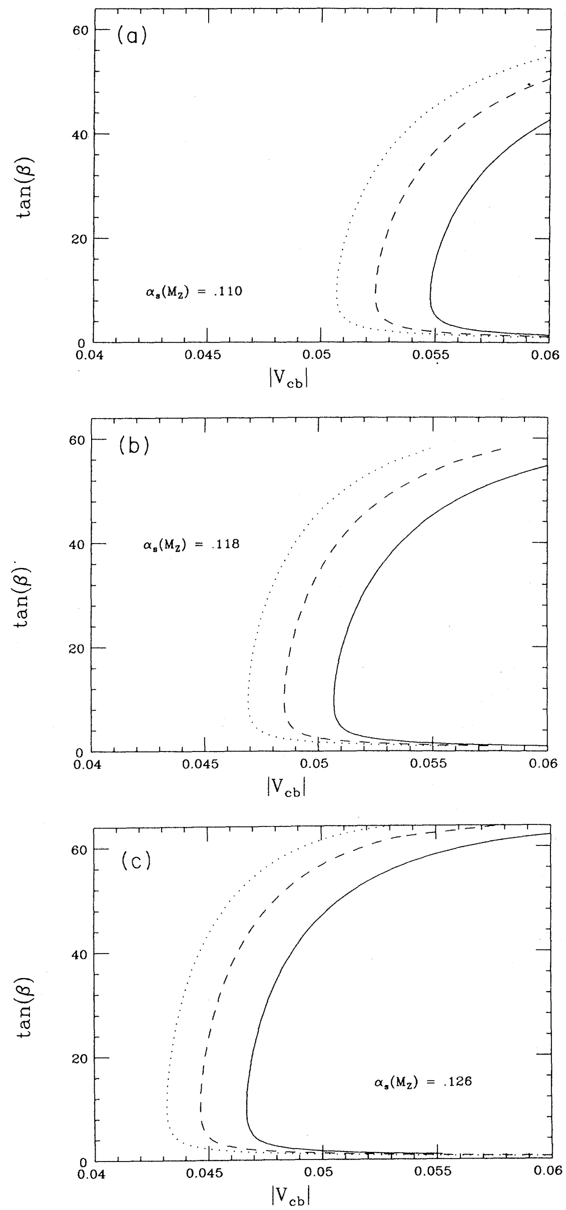

FIG. 2. (a) A plot of $\tan\beta$ vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.110$. On the solid (dashed) [dotted] curve, the modified minimal subtraction scheme ($\overline{\rm MS}$) values of the running quark masses are $m_b(m_b)=4.25$ (4.15) [4.086] GeV and $m_c(m_c)=1.27$ (1.22) [1.186] GeV. (b) A plot of $\tan\beta$ vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.118$. The solid, dashed, and dotted lines correspond to the same quark masses as (a). (c) A plot of $\tan\beta$ vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.126$. The solid, dashed, and dotted lines correspond to the same quark masses as (a).

[1]This relation was first noted by Harvey, Ramond, and Reiss in Ref. [7].

(see Fig. 3). In Fig. 4, we plot the prediction for m_t directly as a function of $|V_{cb}|$.

How constrained are the predicted values of m_t and $\tan\beta$? Having specified m_c, m_b, and α_s, choosing a value for $|V_{cb}|$ in principle determines two discrete values for $\tan\beta$. However, over a large range, $\tan\beta$ is a very sensitive function of $|V_{cb}|$. In addition, the relationship between $\tan\beta$ and $|V_{cb}|$ is affected by uncertainties in α_s, m_b, and m_c. Hence, until we know the values of $|V_{cb}|$, m_c, m_b, and α_s with better precision, $\tan\beta$ is not well determined. For this reason we chose to display our predictions for $\tan\beta$ and m_t as an allowed region where the quantities mentioned above are allowed to vary within the current experimental uncertainties. Moreover, Figs. 2(a)–2(c), 3(a)–3(c), and 4(a)–4(c) show the sensitivity of the predictions to variations in $\alpha_s(m_Z)$ for the three values, 0.110, 0.118, and 0.126. Note, the plots in this paper are for the pole mass of the top quark defined in terms of the running mass by

$$m_t(\text{pole})=m_t(m_t)(1+4\alpha_s/3\pi)\ . \tag{2.3}$$

Let us now consider the theoretical uncertainty in our predictions due to the experimental and/or theoretical uncertainty in $\alpha_s(m_Z)$. Although a seemingly precise value of $\alpha_s(m_Z)$ can be obtained by imposing one-loop unification of the three gauge couplings at a single point $\mu=M_G$ and evolving the strong coupling down to the weak scale, both GUT and weak scale threshold corrections introduce significant theoretical uncertainties in α_s. We therefore allow α_s to vary over the range $\alpha_s=0.118\pm0.008$. The uncertainty in α_s affects the predictions through their dependence on the renormalization factors. For example at fixed $\tan\beta$, the square of $|V_{cb}|$ is proportional to the bottom quark and charm quark Yukawa couplings at the scale $\mu=m_t$ (see Ref. [6]). So for fixed charm and bottom quark masses,

$$|V_{cb}|^2\propto 1/\eta_b\eta_c\ . \tag{2.4}$$

Thus a larger value of α_s gives a smaller value of $|V_{cb}|$. Similarly, $|V_{ub}|/|V_{cb}|$ grows like $\sqrt{\eta_c}$.

The qualitative behavior of the solutions at large values of $\tan\beta$ can be understood by appealing to the solutions obtained previously for small values of $\tan\beta$ and by studying the effect of the b-quark Yukawa coupling on the running of the b/τ ratio. The renormalization group equation for the τ Yukawa coupling does not depend on the top quark Yukawa coupling at one loop. So once we specify values of $\tan\beta$ and $\alpha_s(m_Z)$ the GUT scale input D can be given as a unique function of the parameter A by demanding that the τ lepton mass is 1.78 GeV.[2] The top quark Yukawa coupling can then be determined from the b-quark mass. In general, the top quark Yukawa coupling decreases the b/τ ratio, and a phenomenologically acceptable ratio requires a large top quark Yukawa coupling.

[2]Although the RG equation for the τ Yukawa coupling does not contain the top quark Yukawa coupling, $\lambda_\tau(m_t)$ will in general depend on A because the evolution of the b Yukawa coupling, which contributes to the running of λ_τ, depends on A.

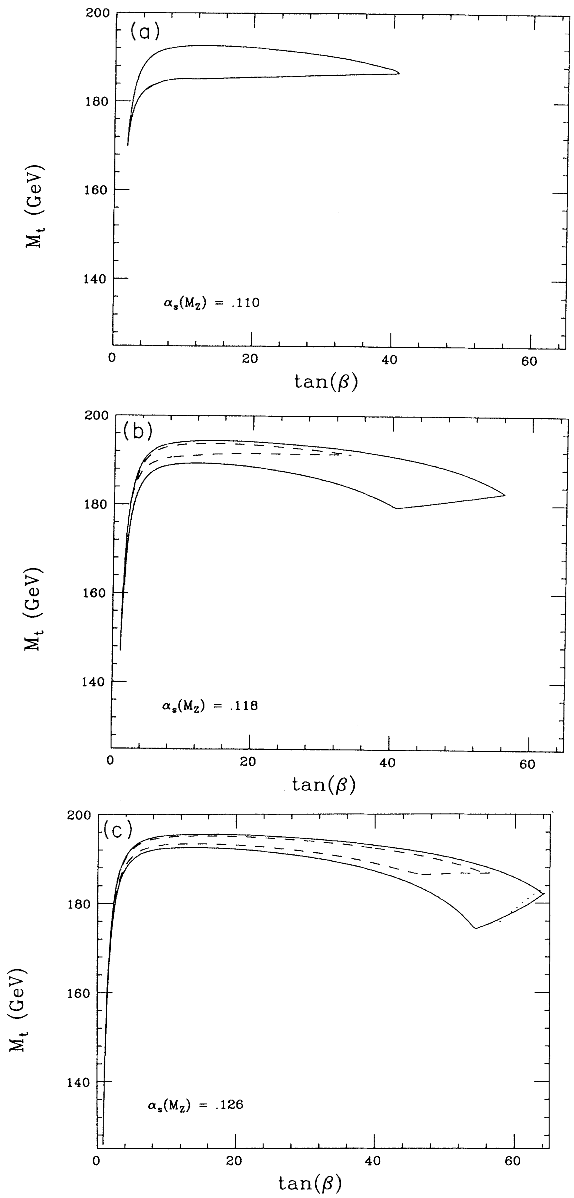

FIG. 3. (a) A plot of the top quark's pole mass m_t vs $\tan\beta$ for $\alpha_s(m_Z)=0.110$; inside the solid curve, $m_b(m_b)=4.25\pm0.164$ GeV, $m_c(m_c)=1.27\pm0.082$ GeV, and $|V_{cb}|\leq0.054$. With these restrictions, the top quark mass is predicted to lie in the range $170. < m_t < 192.6$, while $\tan\beta$ is restricted to $1.85<\tan\beta<41$. The dotted curve near $\tan\beta=60.$ is the prediction when $A=D$. (b) A plot of the top quark's pole mass m_t vs $\tan\beta$ for $\alpha_s(m_Z)=0.118$; inside the dashed (solid) curve, $m_b(m_b)=4.25\pm0.1(\pm0.164)$ GeV, $m_c(m_c)=1.27\pm0.05(\pm0.082)$ GeV, and $|V_{cb}|\leq0.050(\leq0.054)$. With these restrictions, the top quark mass is predicted to lie in the range $181.5<m_t<193.8$ $(147<m_t<194.)$, and $\tan\beta$ is restricted to $2.6<\tan\beta<34.$ $(115<\tan\beta<56.)$. (c) A plot of the top quark's pole mass m_t vs $\tan\beta$ for $\alpha_s(m_Z)=0.126$; inside the dashed (solid) curve, $m_b(m_b)=4.25\pm0.1(\pm0.164)$ GeV, $m_c(m_c)=1.27\pm0.05(\pm0.082)$ GeV, and $|V_{cb}|\leq0.050(\leq0.054)$. With these restrictions, the top quark mass is predicted to lie in the range $1.554<m_t<195$ $(126<m_t<195.5)$, while $\tan\beta$ is restricted to $1.3<\tan\beta<56.4$ $(0.83<\tan\beta<64.3)$. The dotted line gives the prediction for the case $A=D$ with $m_c(m_c)=1.188$ GeV.

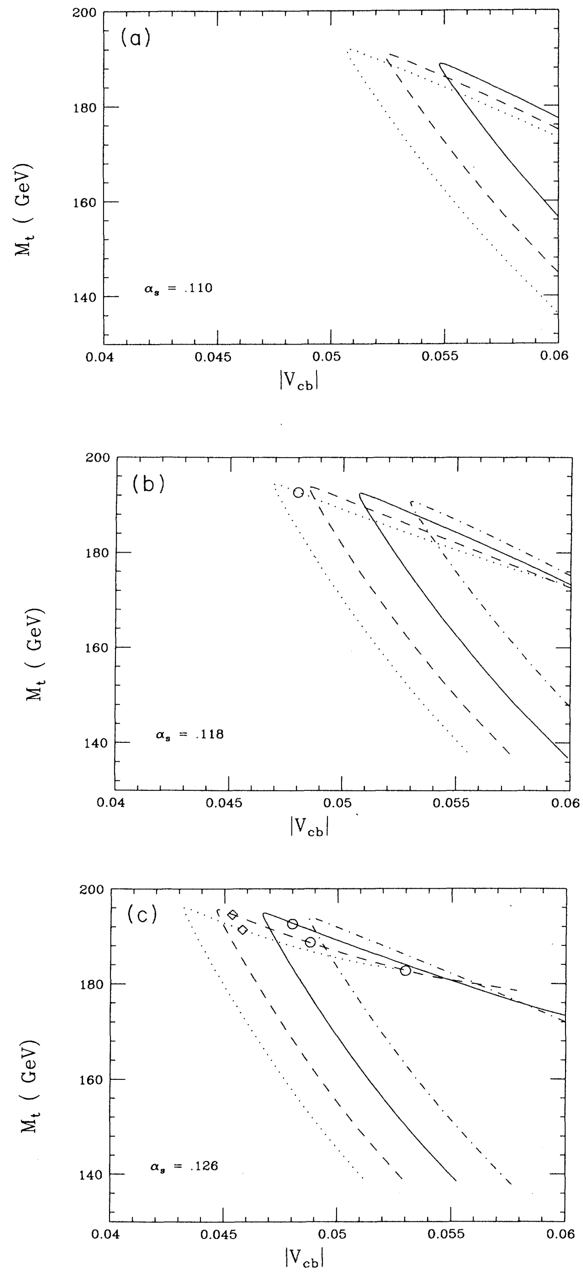

FIG. 4. (a) A plot of the pole mass m_t vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.110$. The dotted, dashed, and solid curves correspond to those in Fig. 2. (b) A plot of the pole mass m_t vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.118$. The dotted, dashed, and solid curves correspond to those in Fig. 2. The additional dotted and dashed curve is for $m_b(m_b)=4.35$ GeV, and $m_c(m_c)=1.32$ GeV. On each curve, the arrows indicate the direction of increasing $\tan\beta$ and monotonically decreasing, GUT scale top Yukawa coupling A. The circles indicate points where $A=2.0$. (c) A plot of the pole mass m_t vs $|V_{cb}|$ for $\alpha_s(m_Z)=0.126$. The dotted, dashed, and solid curves correspond to those of Fig. 2. The additional dotted and dashed curve is for $m_b(m_b)=4.35$ GeV, and $m_c(m_c)=1.32$ GeV. On each curve, the arrows indicate the direction of increasing $\tan\beta$ and monotonically decreasing, GUT scale top Yukawa coupling A. The diamonds (circles) indicate points where $A=2.5$ (2.0).

Let us now define R as the ratio of the b-quark mass to the τ lepton mass. Then

$$\mu\frac{dR}{d\mu}=\frac{R}{16\pi^2}[-d_i g_i^2+\lambda_t^2+3\lambda_\tau^2(R^2-1)] , \qquad (2.5)$$

where the RG constants d_i are defined in Ref. [6]. Because R is larger than unity for most of the RG evolution, a large τ Yukawa coupling tends to decrease the b/τ ratio.[3] So, as $\tan\beta$ is increased, because D must increase to keep the τ mass constant, b/τ decreases. Since b/τ decreases, a smaller top quark Yukawa coupling is needed to maintain a fixed b/τ ratio. Thus at large values of $\tan\beta$ the top quark Yukawa coupling A decreases and so does m_t (Fig. 3). In addition, as A decreases, $|V_{cb}|$ increases, which results in an upper limit on $\tan\beta$ (Fig. 2). These relationships can also be seen in Fig. 4 which displays the prediction for m_t in terms of $|V_{cb}|$. The smallest values of $|V_{cb}|$ and largest values of m_t occur for large α_s and small m_b. However, large values of α_s and small values of m_b require large values for the GUT scale top quark Yukawa coupling A. For the range of parameters studied in this paper $A<3$. A perturbative one-loop calculation becomes unreliable for larger α_s and smaller m_b.

Can we reduce the number of parameters at the GUT scale? In Table I we give some sample input at the GUT scale.

The large mass hierarchy between similarly charged quarks in different families requires $A \gg B \gg C$ and $D \gg E \gg F$. However, since the up and down quarks obtain mass from the vacuum expectation values of different Higgs doublets, there is *a priori* no connection between A,B,C and D,E,F. An extremely interesting question is whether the number of predictions of this scheme can be increased by arranging for relations between the Yukawa couplings of the up and down sectors. A simple such relation is $A=D$. This occurs in SO(10) models which have a single decouplet generating the masses of the third generation provided that both light SU(2) doublets lie predominantly in this decouplet.

If attention is limited to the heaviest generation, the requirement that the three Yukawa couplings are equal at the unification scale leads to a prediction for the top mass [10]: there are two parameters (λ and $\tan\beta$) and three observables. Unfortunately the prediction is very sensitive to α_s: m_t increases from 110 GeV to near 180 GeV as α_s increases from 0.10 to 0.12. However, when all three generations are considered the third generation parameters cannot be treated in isolation, since they affect other observables, such as V_{cb}. Setting $A=D$, i.e., making $\tan\beta$ very large, leads to large values of V_{cb}, as can be seen from Fig. 2. Hence $A=D$ is only consistent with large α_s. This considerably narrows our parameter space: $\tan\beta=60.6\pm3$, $m_t=179\pm4$ GeV, $\alpha_s\geq 0.123$, and $|V_{cb}|\geq 0.052$. Since the number of free parameters has been reduced by one, $|V_{cb}|$ is now a prediction of the theory rather than an input.

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[3]When $A \lesssim 1.4$, $R \geq 1$ over the entire range of the RG scale μ.

TABLE I. Sample input at GUT scale.

$\tan\beta$	A	B	C	D	E	F	ϕ
1.0	1.7	0.070	0.0002	0.01	0.0002	0.000 04	1.2
10.0	2.2	0.076	0.000 14	0.070	0.001	0.0003	1.2
60.0	1.3	0.05	0.001	1.46	0.014	0.0033	1.5

Finally, we mention the impact of this framework on radiative electroweak symmetry breaking in supersymmetric theories. Recently, Ananthanarayan, Lazarides, and Shafi have demonstrated that radiative electroweak symmetry breaking can be accomplished in the minimal supersymmetric model when all three third generation Yukawa couplings are equal at the GUT scale [11]. Since the framework studied in this paper with $A = D$ tightly constrains m_t and $\tan\beta$ it leads to a very predictive heavy sparticle mass spectrum.

III. CONCLUSION

In this paper we have given a general one-loop analysis of a predictive framework for fermion masses and mixing angles. This extends the results of Dimopoulos, Hall, and Raby (DHR) [6] to large $\tan\beta$. The results of this work are shown in the figures. Figures 2 and 4 show how the predictions for $\tan\beta$ and m_t depend on the input V_{cb}. In particular, Fig. 2 shows that, for any input which DHR found led to an acceptable $\tan\beta$, there is also an additional large $\tan\beta$ solution. Figure 3 shows that this large $\tan\beta$ region always has a top quark mass in the range 185 ± 10 GeV, which is clearly much more restrictive than in the region of lower $\tan\beta$.

The figures also provide an illustration of how the predictions for $\tan\beta$ and m_t depend on the input m_c, m_b, and especially α_s. It is because of the uncertainties in the values of these inputs that $\tan\beta$ can vary so much. It is worth stressing that increasing $\alpha_s(m_Z)$ from 0.110 to 0.126 can reduce m_t from 170 GeV to 126 GeV.

Further restricting the framework studied by DHR by imposing a relationship between the Yukawa couplings of the up and down sectors, namely, setting $A = D$, produces a scheme where the fourteen flavor parameters are predicted with just seven inputs. In this case V_{cb} is no longer an input, but is predicted by the theory. This very predictive scheme can only be correct if α_s and V_{cb} are both large and if $m_t = 179. \pm 4$ GeV.

Note added. After this work was completed, we received a preprint [12] in which a similar analysis has been performed.

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