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Flavor Physics and the Triviality Bound on the Higgs Mass

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Abstract

The triviality of the scalar sector of the standard one-doublet Higgs model implies that this model is only an effective low-energy theory valid below some cut-off scale Λ. The underlying high-energy theory must include flavor dynamics at a scale of order Λ or greater in order to give rise to the different Yukawa couplings of the Higgs to ordinary fermions. This flavor dynamics will generically produce flavor-changing neutral currents and non-universal corrections to $Z \to b\bar{b}$. We show that the experimental constraints on the neutral D-meson mass difference imply that Λ must be greater than of order 21 TeV. We also discuss bounds on Λ from the constraints on extra contributions to the K_L-K_S mass difference and to the coupling of the Z boson to b-quarks. For theories defined about the infrared-stable Gaussian fixed-point, we estimate that this lower bound on Λ yields an upper bound of approximately 460 GeV on the Higgs boson's mass, independent of the regulator chosen to define the theory.

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1   Introduction

The triviality [1] of the scalar sector of the standard one-doublet Higgs model implies that this theory is only an effective low-energy theory valid below some cutoff scale Λ. Physically this scale marks the appearance of new strongly-interacting symmetry-breaking dynamics, examples of which include "top-mode" standard models [2] and composite Higgs models [3]. As the Higgs mass, M_H, increases, the upper bound on the scale of new physics decreases. Thus, if one requires that M_H/Λ be small enough to afford the effective Higgs theory some range of validity (or to minimize the effects of regularization in the context of a calculation in the scalar theory), one arrives at the conventional upper limit on M_H of approximately 700 GeV [4].

In a previous paper [5], two of us discussed how constraints on custodial symmetry violation affect the upper bound on the Higgs mass. We noted that the underlying high-energy physics must provide some custodial symmetry violation in order to explain the large mass splitting between the top and bottom quarks. This enabled us to show that the experimental constraint on the amount of custodial symmetry violation, $|\Delta\rho_*| = \alpha|T|$, implies that the scale Λ must be greater than of order 7.5 TeV, and we argued that the bound is regularization-independent.[1]

This lower bound on the scale Λ yielded [5] an upper limit of approximately 550 GeV on the Higgs boson's mass.

Similarly, regardless of the precise nature of the underlying strongly-interacting physics, there must be flavor dynamics at a scale of order Λ or greater that gives rise to the different Yukawa couplings of the Higgs boson to ordinary fermions. As in extended technicolor theories [9, 10], this flavor dynamics will generically cause flavor-changing neutral currents and non-universal corrections to the decay $Z \to b\bar{b}$. In this note we derive a lower bound on Λ from the experimental constraints on extra contributions to the neutral meson mass differences and to the coupling of the Z boson to b-quarks. We then estimate the upper limit on the Higgs boson's mass corresponding to this lower bound on Λ.

Since the operators responsible for generating quark masses and for causing flavor-changing neutral currents violate flavor symmetries differently [11], in principle one could construct a theory with an approximate GIM symmetry [11, 12, 13]. In such models, flavor-changing neutral currents would be suppressed but different quarks would still receive different masses. A theory of this type which included a light scalar state (unlike the examples [11, 12, 13]) would be able to evade the flavor-changing neutral current limits discussed here. However, such models would still [10] be subject to the bounds we find from $Z \to b\bar{b}$ and could also give rise to potentially dangerous contributions to other processes [14].

Implicitly assumed in these bounds is the naive scaling that one expects near

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[1]The S parameter [6] also provides a limit on Λ, but it is weaker than that from T. The only dimension-6 operator that contributes [7] to S is $\frac{1}{\Lambda^2}\left\{[D_\mu, D_\nu]\,\phi\right\}^\dagger [D_\mu, D_\nu]\,\phi$. Since this implies $S = 2\pi v^2/\Lambda^2$, the 95 % c.l. $S \lesssim 0.23$ [8] yields $\Lambda \gtrsim 1.3\,\mathrm{TeV}$.

the infrared-stable Gaussian fixed point of scalar field theory. Other fixed points with very different scaling behavior may also exist. In this case, the bounds we discuss here would not apply. However, as discussed in [5], to construct a phenomenologically viable theory of a strongly-interacting Higgs sector it is not sufficient to simply construct a theory with a heavy Higgs boson. To be consistent with the experimental bound on $|\Delta\rho_*|$, one must also ensure that all potentially custodial-isospin-violating operators remain irrelevant. For this reason, we expect constructing a phenomenologically-acceptable non-trivial scalar electroweak symmetry breaking sector to be difficult. To our knowledge, no acceptable model of this sort has been proposed.

2   Flavor Physics and the Higgs Couplings

In what follows, we consider a theory with an arbitrary strongly-interacting sector which reduces at low energies to the one-Higgs-doublet standard model. Our goal is to understand how the underlying strongly-interacting dynamics would manifest itself in low-energy flavor physics.

To estimate the sizes of various effects of the underlying physics, we rely on dimensional analysis. As noted by Georgi [15], a theory[2] with light scalar particles belonging to a single symmetry-group representation depends on two parameters: Λ, the scale of the underlying physics, and f (the analog of f_π in QCD), which measures the amplitude for producing the scalar particles from the vacuum. Our estimates of the sizes of the low-energy effects of the underlying physics will depend on the ratio $\kappa \equiv \Lambda/f$, which determines the sizes of coupling constants in the low-energy theory. The value of κ is expected to fall between 1 and 4π. For example, in QCD we find that the ρ-coupling is $g_\rho = \mathcal{O}(\kappa) \approx 6$. In a QCD-like theory with N_c colors and N_f flavors one expects [16] that
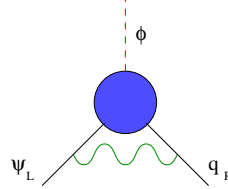
$$\kappa \approx \min\left(\frac{4\pi a}{N_c^{1/2}}, \frac{4\pi b}{N_f^{1/2}}\right) \ , \tag{2.1}$$

where a and b are constants of order 1. In the results that follow, we will display the dependence on κ explicitly; when giving numerical examples, we set κ equal to the geometric mean of 1 and 4π, *i.e.* $\kappa \approx 3.5$.

We begin by considering what the observed masses of the ordinary fermions imply about the underlying physics. Providing the different masses of the fermions requires flavor physics (analogous to extended-technicolor interactions (ETC) [9, 17]) which couples the left-handed quark doublets ψ_L and right-handed singlets q_R to the strongly-interacting "preon" constituents of the Higgs doublet. At low energies,

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[2]These dimensional estimates only apply if the low-energy theory, when viewed as a scalar field theory, is defined about the infrared-stable Gaussian fixed-point. As discussed above, we expect this to be the case.

these interactions produce the quark Yukawa couplings. Assuming, for simplicity, that these new flavor interactions are gauge interactions with gauge coupling g and gauge boson mass M, dimensional analysis [18] allows us to estimate that the size of the resulting Yukawa coupling is [3] of order $(g^2/M^2)(\Lambda^2/\kappa)$, i.e.

$$\Rightarrow \frac{g^2}{M^2}\frac{\Lambda^2}{\kappa}\bar{q}_R\phi\psi_L \ . \tag{2.2}$$

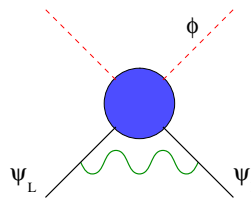In order to give rise to a quark mass m_q, the Yukawa coupling must be equal to

$$\frac{\sqrt{2}m_q}{v} \tag{2.3}$$

where $v \approx 246$ GeV. This implies[3]

$$\Lambda \gtrsim \frac{M}{g}\sqrt{\sqrt{2}\kappa\frac{m_q}{v}} \ . \tag{2.4}$$

Thus, if we set a lower limit on M/g from low-energy flavor physics, eqn.(2.4) will give a lower bound on Λ.

The high-energy flavor physics responsible for the generation of the quark-preon couplings *must* distinguish between different flavors so as to give rise to the different masses of the corresponding fermions. In addition to the Higgs-fermion coupling discussed above, the flavor physics will also give rise to flavor-specific couplings of ordinary fermions to themselves [9] and of weak currents of ordinary fermions to weak currents of preons [10]. Such interactions will cause potentially visible effects on flavor physics at low energies. For example, the interaction between weak currents of preons and ordinary fermions gives rise to an operator that can alter the $Zb\bar{b}$ vertex. If the new gauge interactions commute with $SU(2)_W$, *i.e.* if the gauge bosons do not carry weak charge, using dimensional analysis we find the coefficient of the appropriate operator in the effective Lagrangian to be

$$\Rightarrow -2\frac{g^2}{M^2}\left[(D_\mu\phi)^\dagger i\frac{\tau_3}{2}\phi - \phi^\dagger i\frac{\tau_3}{2}D_\mu\phi\right]\bar{q}_L\gamma^\mu\frac{\tau_3}{2}q_L \ . \tag{2.5}$$

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[3]Because the low-energy theory is (approximately) the standard model, unitarity in the scattering amplitude $q\bar{q} \to W_L W_L$ is ensured due to Higgs Boson exchange. In this case, unlike ref. [19], there is no *upper bound* on the scale M/g.

After spontaneous symmetry breaking, this shifts the coupling of the Z to $q\bar{q}$

$$\delta g_L^q = -\frac{g^2}{M^2}\frac{v^2}{2}T_3^q \ , \tag{2.6}$$

where $T_3^q = \pm\frac{1}{2}$ is the weak-isospin of the quark. Note that, as in the case of conventional "commuting" ETC [10] models, the sign of the coupling shift is prescribed and the shift tends to reduce the decay-width of Z to each quark.

The new current-current interactions among ordinary fermions, on the other hand generically give rise to flavor-changing neutral currents (as previously noted in [9] for the case of ETC theories) that affect Kaon, D-meson, and B-meson physics. For instance, consider the interactions responsible for the s-quark mass. Through Cabibbo mixing, these interactions must couple to the d-quark as well. This will generally give rise to the interactions

$$
\begin{aligned}
\mathcal{L}_{eff} =\ & -(\cos\theta_L^s \sin\theta_L^s)^2 \frac{g^2}{M^2}(\overline{s}_L\gamma^\mu d_L)(\overline{s}_L\gamma_\mu d_L) \\
& -(\cos\theta_R^s \sin\theta_R^s)^2 \frac{g^2}{M^2}(\overline{s}_R\gamma^\mu d_R)(\overline{s}_R\gamma_\mu d_R) \\
& -\cos\theta_L^s \sin\theta_L^s \cos\theta_R^s \sin\theta_R^s \frac{g^2}{M^2}(\overline{s}_L\gamma^\mu d_L)(\overline{s}_R\gamma_\mu d_R) \ ,
\end{aligned}
\tag{2.7}
$$

where the coupling g and mass M are of the same order as those in the interactions which ultimately give rise to the s-quark Yukawa coupling in eqn. (2.2), and the angles θ_L^s and θ_R^s represent the relation between the gauge eigenstates and the mass eigenstates. The operators in eqn. (2.7) will clearly affect neutral Kaon physics. Similarly, the interactions responsible for other quarks' masses will give rise to operators that contribute to mixing and decays of various mesons.

3   Constraints on Λ from Flavor Physics

3.1   Flavor-Changing Neutral Currents: ΔS and ΔB

To start, let us consider the four-fermion interactions in eqn. (2.7), which will alter the predicted value of the $K_L - K_S$ mass difference. Using the vacuum-insertion approximation [20], we can estimate separately how much the purely left-handed (LL), purely right-handed (RR) and mixed (LR) current-current operators contribute. Requiring each contribution to be less than the observed mass difference Δm_K, we find the bounds

$$\left(\frac{M}{g}\right)_{\text{LL,RR}} \quad \gtrsim \quad f_K\left(\frac{2m_K B_K}{3\Delta m_K}\right)^{1/2} \cos\theta_{L,R}^s \sin\theta_{L,R}^s \tag{3.1}$$

$$\approx \quad 0.92\times 10^3\,\text{TeV}\,\cos\theta_{L,R}^s \sin\theta_{L,R}^s \tag{3.2}$$

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from the first two operators in eqn. (2.7), and

$$\left(\frac{M}{g}\right)_{\text{LR}} \gtrsim f_K \left\{ \frac{m_K B_K'}{3\Delta m_K} \left[\frac{m_K^2}{(m_s + m_d)^2} - \frac{3}{2} \right] \right\}^{1/2} (\cos\theta_L^s \sin\theta_L^s \cos\theta_R^s \sin\theta_R^s)^{1/2} \quad (3.3)$$

$$\approx 1.4 \times 10^3 \,\text{TeV} \, (\cos\theta_L^s \sin\theta_L^s \cos\theta_R^s \sin\theta_R^s)^{1/2} \quad (3.4)$$

from the last operator in eqn. (2.7). In evaluating these expressions, we have used $f_K \approx 113$ MeV, the "bag" factors $B_K, B_K' \sim 0.7$, and $m_s + m_d \sim 200$ MeV. In order to produce the observed $d - s$ mixing, we expect that at least one of the angles θ_L^s, θ_R^s is of order the Cabibbo angle, θ_C. Then we find from any one operator

$$\frac{M}{g} \gtrsim 200 \,\text{TeV} \ . \quad (3.5)$$

From eqn. (2.4) it follows that

$$\Lambda \gtrsim 6.8 \,\text{TeV} \sqrt{\kappa \left(\frac{m_s}{200 \,\text{MeV}} \right)} \ . \quad (3.6)$$

For $\kappa \approx 3.5$, this yields a lower bound of approximately 13 TeV on Λ.

Typically, in addition to the operators in eqn. (2.7) there will be flavor-changing operators which are products of color-octet currents[4]. At least in the vacuum-insertion approximation, the matrix elements of products of color-octet currents are enhanced relative to those shown in (2.7) by a factor of 4/3 for the LL and RR operators and a factor of approximately 7 for the LR operator. Furthermore, because left-handed quarks are weak doublets flavor physics associated with the c-quark mass may also contribute to $\Delta S = 2$ interactions. If so, one would replace m_s with m_c in eqn. (3.6), yielding a lower bound on Λ of order $20\sqrt{\kappa}$ TeV.

Furthermore, in the absence of additional superweak interactions to give rise to CP-violation in K-mixing (ε), the flavor interactions responsible for the s-quark Yukawa couplings must violate CP at some level. In this case the the bounds on the scale M/g are yet stronger. Recalling that

$$\text{Re}\,\varepsilon \approx \frac{\text{Im}M_{12}}{2\,\Delta M} \lesssim 1.65 \times 10^{-3} \, , \quad (3.7)$$

and assuming that there are phases of order 1 in the operators shown in eqn. (2.7), we find the bound

$$\frac{M}{g} \gtrsim 3.5 \times 10^3 \,\text{TeV} \ , \quad (3.8)$$

yielding a lower bound on Λ of order $120\sqrt{\kappa}$ TeV. For these reasons, the bounds from eqn. (3.6) may be conservative.

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[4] Note that it is likely that color must be embedded in the flavor interactions in order to avoid possible Goldstone bosons [9] and large contributions to the S parameter [6].

A similar analysis of the link between the b-quark mass and $B_d - \overline{B}_d$ mixing yields the bounds

$$\left(\frac{M}{g}\right)_{\text{LL,RR}} \gtrsim f_B V_{td} \left(\frac{2m_B B_B}{3\,\Delta m_B}\right)^{1/2} \approx 6.5\,\text{TeV} \tag{3.9}$$

$$\left(\frac{M}{g}\right)_{\text{LR}} \gtrsim f_B V_{td} \left\{\frac{m_B B_B'}{3\,\Delta m_B}\left|\frac{m_B^2}{(m_b+m_d)^2}-\frac{3}{2}\right|\right\}^{1/2} \approx 1.6\,\text{TeV} \tag{3.10}$$

on the interactions associated with generating the b-quark Yukawa couplings. Here we have used $f_B\sqrt{B_B} = 0.2$ GeV, $B_B = B_B'$, $\Delta m_B \approx 3.3\times10^{-10}$ MeV, $m_b+m_d = 4.5$ GeV, and have assumed that all b-d mixing angles are of order $V_{td} = \mathcal{O}(10^{-2})$. Applying eqn. (2.4) in the case of the b-quark, we find the weaker bound

$$\Lambda \gtrsim 1.9\,\text{TeV}\sqrt{\kappa\left(\frac{m_b}{4.5\,\text{GeV}}\right)} \ . \tag{3.11}$$

If the flavor physics associated with t-quark mass generation contributes to $\Delta B = 2$ interactions, one should replace m_b with m_t, yielding a bound of order $12\sqrt{\kappa}$ TeV.

Studying the process $b \to s\gamma$ gives no further constraint on the scale of new physics at present. The uncertainty in the hadronic matrix elements is about 25% [21], whereas the direct correction to the standard model rate for $b \to s\gamma$ from heavy gauge bosons, such as in ETC models, is about 10 % [22].

3.2 Flavor-Changing Neutral Currents: ΔC

Usually, the strongest constraints on nonstandard physics from flavor-changing neutral currents come from processes involving Kaons or B-mesons, like those considered above. In the present case, however, the constraints from $D^0 - \overline{D}^0$ mixing are also important because the c-quark is heavier than the s-quark, while the $u-c$ mixing is as large as the $d-s$ mixing.

Again, there are contributions to D-meson mixing from the color-singlet products of currents analogous to those in eqn. (2.7). The purely left-handed or right-handed current-current operators yield

$$\left(\frac{M}{g}\right)_{\text{LL,RR}} \gtrsim f_D \left(\frac{2m_D B_D}{3\Delta m_D}\right)^{1/2} \cos\theta_{L,R}^c \sin\theta_{L,R}^c \approx 120\,\text{TeV} \ , \tag{3.12}$$

where we have used the limit on the neutral D-meson mass difference, $\Delta m_D \lesssim 1.4\times 10^{-10}$ MeV [8], and $f_D\sqrt{B_D} = 0.2$ GeV, $\theta_{L,R}^c \approx \theta_C$. The bound on the scale of the underlying strongly-interacting dynamics follows from eqn. (2.4):

$$\Lambda \gtrsim 11\,\text{TeV}\sqrt{\kappa\left(\frac{m_c}{1.5\,\text{GeV}}\right)} \ , \tag{3.13}$$

so that $\Lambda \gtrsim 21$ TeV for $\kappa \approx 3.5$.

The $\Delta C = 2$, LR product of color-singlet currents gives a weaker bound than eqn. (3.13) but the LR product of color-octet currents,

$$\mathcal{L}_{eff} = -\cos\theta_L^c \sin\theta_L^c \cos\theta_R^c \sin\theta_R^c \frac{g^2}{M^2}(\overline{c}_L\gamma^\mu T^a u_L)(\overline{c}_R\gamma_\mu T^a u_R) , \qquad (3.14)$$

where T^a are the generators of $SU(3)_C$, gives a stronger bound:

$$\left(\frac{M}{g}\right)_{\mathrm{LR}} \gtrsim \frac{4f_D}{3(m_c + m_u)}\left(\frac{m_D^3 B_D'}{\Delta m_D}\right)^{1/2}(\cos\theta_L^c \sin\theta_L^c \cos\theta_R^c \sin\theta_R^c)^{1/2} \quad (3.15)$$

$$\approx 240\,\mathrm{TeV}\left(\frac{1.5\,\mathrm{GeV}}{m_c}\right) , \qquad (3.16)$$

corresponding to

$$\Lambda \gtrsim 22\,\mathrm{TeV}\sqrt{\kappa\left(\frac{1.5\,\mathrm{GeV}}{m_c}\right)} . \qquad (3.17)$$

3.3 Corrections to $Z \to b\bar{b}$

As noted in section 2, the flavor interactions typically produce non-universal corrections to the couplings of the the Z to ordinary fermions, eqn. (2.6). In conventional models, where $SU(2)_W$ is not embedded in the new interactions, the effect of these interactions is to *decrease* the width of the Z to each fermion. Because left-handed quarks transform as weak doublets and the left-handed b-quark is (predominantly) in a doublet with the t-quark, the flavor interactions associated with the top-quark mass [10] can cause potentially important corrections to the $Zb\bar{b}$ coupling.

The decay width of the Z into b-quarks is most conveniently measured in terms of the ratio, R_b, of the b-quark partial width to the hadronic partial width. A change δg_L^b of the Z boson's coupling to b-quarks would result in a change in R_b relative to the standard model of

$$\delta R_b \approx R_b(1 - R_b)\frac{2g_L^b \delta g_L^b}{(g_L^b)^2 + (g_R^b)^2} \approx -0.774\,\delta g_L^b \quad . \qquad (3.18)$$

From eqns. (2.4), (2.6) and (3.18) we find

$$\Lambda = \left(\frac{m_t v}{2\sqrt{2}}\frac{0.774}{(-\delta R_b)}\kappa\right)^{1/2} \qquad (3.19)$$

$$\approx 0.11\,\mathrm{TeV}\left(\frac{\kappa}{-\delta R_b}\right)^{1/2} . \qquad (3.20)$$

7

Note that a conventional model only accommodates a *decrease* in R_b. For this reason the limits we can place on Λ are extremely sensitive to the bounds on negative values of δR_b. The current "best fit" to LEP and SLD data yields the value [23]

$$R_b = 0.2178 \pm 0.0011 \ ,$$

as compared to the standard model prediction (for $m_t = 172 \pm 6$ GeV [24]) of

$$R_b^{\text{sm}} = 0.2158 \ .$$

These imply

$$\delta R_b = 0.0020 \pm 0.0011 \ . \tag{3.21}$$

At 95% confidence level $-\delta R_b|_{2\sigma} \leq 0.0002$, corresponding to

$$\Lambda \gtrsim 7.7 \,\text{TeV}\sqrt{\kappa} \ , \tag{3.22}$$

(14 TeV for $\kappa \approx 3.5$) whereas at 99.7% confidence level $-\delta R_b|_{3\sigma} \leq 0.0013$, corresponding to

$$\Lambda \gtrsim 3.1 \,\text{TeV}\sqrt{\kappa} \ . \tag{3.23}$$

Given the sensitivity to the confidence level, we view the bound in eqn. (3.22) as less "robust" than the bounds from $K - \overline{K}$ or $D - \overline{D}$ mixing (eqns. (3.6) and (3.13)).

4 Higgs Mass Limits

Because of triviality, a lower bound on the scale Λ yields an upper limit on the Higgs boson's mass. A rigorous determination of this limit would require a non-perturbative calculation of the Higgs mass in an $O(4)$-symmetric theory subject to the constraint on Λ. Here we provide an estimate of this upper limit by naive extrapolation of the lowest-order perturbative result[5]. Integrating the lowest-order beta function for the Higgs self-coupling λ,

$$\beta(\lambda) = \mu \frac{d\lambda}{d\mu} = \frac{3}{2\pi^2}\lambda^2 + \dots \ , \tag{4.1}$$

we find

$$\frac{1}{\lambda(\mu)} - \frac{1}{\lambda(\Lambda)} = \frac{3}{2\pi^2} \ln \frac{\Lambda}{\mu} \ . \tag{4.2}$$

Using the relation $m_H^2 = 2\lambda(m_H)v^2$ we find the relation

$$m_H^2 \ln\left(\frac{\Lambda}{m_H}\right) \leq \frac{4\pi^2 v^2}{3} \ . \tag{4.3}$$

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[5]The naive perturbative bound has been remarkably close to the non-perturbative estimates derived from lattice Monte Carlo calculations [4].

The lower bounds on Λ from section 3 may be combined with eqn. (4.3) to yield corresponding upper bounds on m_H. The bound $\Lambda > 13$ TeV given by the contribution of the $\Delta S = 2$ product of color-singlet currents to the $K_L - K_S$ mass difference, eqn. (3.6), in the case $\kappa \approx 3.5$, results in the limit[6] $m_H \lesssim 490$ GeV. The bound $\Lambda \gtrsim 21$ TeV, given by the contribution of the $\Delta C = 2$, LL or RR product of color-singlet currents to the neutral D-meson mass difference, eqn. (3.13), yields $m_H \lesssim 460$ GeV. Limits from the contributions of color-octet currents or from the relationship between m_c and Δm_K would be even more stringent. Finally, if the flavor interactions responsible for the s-quark Yukawa coupling also generate CP-violation in Kaon mixing and there are phases of order 1 in the interactions in eqn. (2.7), the resulting bound $\Lambda > 220$ TeV would yield a Higgs mass limit of 350 GeV.

5 Conclusions

Because of triviality, theories with a heavy Higgs boson are effective low-energy theories valid below some cut-off scale Λ. The underlying high-energy theory must include flavor dynamics at a scale of order Λ or greater in order to produce the different Yukawa couplings of the Higgs to ordinary fermions. This flavor dynamics will generically give rise to flavor-changing neutral currents and non-universal corrections to the decay $Z \to b\bar{b}$. In this note we showed that satisfying the experimental constraints on extra contributions to Δm_K, Δm_D, and R_b requires that the scale of the associated flavor dynamics exceed certain lower bounds. At the same time, the new physics must provide sufficiently large Yukawa couplings to give the quarks their observed masses. In order to give rise to a sufficiently large s-quark Yukawa coupling, we showed that Λ must be greater than of order 13 TeV, while in the case of the c-quark the bound is even more stringent, $\Lambda \gtrsim 21$ TeV. For theories defined about the infrared-stable Gaussian fixed-point, we estimated that this lower bound on Λ yields an upper limit of approximately 460 GeV on the Higgs boson's mass, independent of the regulator chosen to define the theory.

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[6]If $\kappa \approx 4\pi$, Λ would have to be greater than 24 TeV, yielding an upper limit on the Higgs boson's mass of 450 GeV. If $\kappa \approx 1$, Λ would be greater than 6.8 TeV, yielding the upper limit $m_H \lesssim 570$ GeV.

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