Phenomenological consequences of an enhanced top-quark Yukawa coupling

Marc Sher* and Dennis Silverman

Department of Physics, University of California, Irvine, Irvine, California 92717
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In models with more than one Higgs doublet, the Yukawa couplings of the d-type (u-type) quarks are changed by a factor A_d (A_u), which is often a ratio of vacuum expectation values. Abbott, Sikivie, and Wise showed that the K_L-K_S mass difference places stringent constraints on A_u ($A_u \lesssim 10$ for a charged-Higgs-boson mass of m_W); however, this bound is very sensitive to the charged-Higgs-boson mass and to small Kobayashi-Maskawa mixing angles. We note that if the enhancement is greater than 4—5, then the top quark's Yukawa coupling will exceed its strong coupling, even if $m_t \sim 35$ GeV. The effects of this enhancement on the e^+e^- cross section, on energy levels, leptonic widths, and decay rate of t-quarkonium, and on top-quark decays are discussed; the former two effects are sensitive to neutral-scalar masses only, the latter to the charged-Higgs-boson mass; all of the effects are insensitive to small mixing angles. We also note that the best limit on A_d comes from recent data on the semileptonic branching ratio of b quarks.

In the simplest extension of the standard electroweak model, the Higgs sector is expanded to include two Higgs doublets Φ_1 and Φ_2. In recent years, two-doublet models have increased in popularity; the simplest supersymmetric models and models with a Peccei-Quinn symmetry all contain two doublets. A feature of such models is the existence of two vacuum expectation values x and y, where the "standard" vacuum value $\sigma = 246$ GeV is given by $(x^2+y^2)^{1/2}$. The ratio x/y is undetermined. As the phenomenology of Higgs bosons in these models critically depends on this ratio, it is of interest to find phenomenological limits to its value. Abbott, Sikivie, and Wise (ASW) noted[1] that stringent bounds on x/y could be found from the K_L-K_S mass difference. The results depend very sensitively on the charged-Higgs-boson mass and on small Kobayashi-Maskawa (KM) mixing angles; for $m_H \sim m_W$, they found that $x/y \lesssim 10$. The result, however, weakens considerably for larger Higgs-boson masses. (In many models, the charged Higgs boson is heavier than some of the neutral Higgs bosons.) It would be useful to find other effects which are either insensitive to small KM angles or are sensitive to neutral-Higgs-boson masses instead of the charged-Higgs-boson mass. In this paper we point out that observations of the top quark will immediately provide a much more stringent bound. In this simplest extension of the standard model, if x/y were greater than about 5, then the top quark's Yukawa coupling, even if its mass is only 35 GeV, will exceed the top quark's gluon coupling, leading to interesting phenomenological consequences.

In the two-Higgs-doublet model, there are five physical Higgs scalars: a charged scalar $\chi^{\pm}$, a neutral pseudoscalar χ^0, and two neutral scalars ϕ_1 and ϕ_2. As discussed by ASW, there are two ways to couple the Higgs doublets to quarks without very large flavor-changing neutral currents: (i) couple one doublet, Φ_1, to all quarks and the other, Φ_2, to no quarks (using a discrete symmetry)[2] or (ii) couple Φ_1 to u-type quarks and Φ_2 to d-type quarks. The latter choice occurs automatically in all supersymmetric

theories and in all models with Peccei-Quinn symmetry, thus we will concentrate on that choice (it would be easy to generalize our results to the other choice). Since we are dealing with the top quark, mixing in the mass matrix will be ignored, for simplicity. The couplings of the third-generation quarks to the Higgs scalars are

$$\frac{g}{\sqrt{2}m_W}\chi^+ \left[m_t \frac{x}{y}\bar{t}(1-\gamma_5)b + m_b \frac{y}{x}\bar{t}(1+\gamma_5)b \right] + \text{H.c.}$$
$$- \frac{ig}{2m_W}\chi^0 \left[m_t \frac{x}{y}\bar{t}\gamma_5 t + m_b \frac{y}{x}\bar{b}\gamma_5 b \right]$$
$$+ \frac{g}{2m_W}\phi_1 \left[-\frac{\sigma}{y}m_t\bar{t}t\cos\theta + \frac{\sigma}{x}m_b\bar{b}b\sin\theta \right]$$
$$- \frac{g}{2m_W}\phi_2 \left[\frac{\sigma}{y}m_t\bar{t}t\sin\theta + \frac{\sigma}{x}m_b\bar{b}b\cos\theta \right],$$

(1)

where θ is a mixing angle between the neutral scalars. Note that if $y \gg x$ ($x \gg y$), the couplings of the d-type (u-type) quarks are greatly enhanced. In the standard model, the top-quark Yukawa coupling is $g_Y = g m_t/\sqrt{2}m_W$, so $\alpha_Y \equiv g_Y^2/4\pi \sim \frac{1}{300}$ for $m_t \sim 35$ GeV. If g_Y is enhanced by a factor of 6, then the Yukawa coupling will equal the strong coupling; if it is enhanced by a factor of 17, then it will become unity. A large Yukawa coupling will have several noticeable effects in (i) the total $e^+e^- \rightarrow$ hadron cross section, (ii) the energy levels and decay of t-quarkonium, and (iii) top-quark decays. The first two will be sensitive to neutral scalars, the third to charged scalars (but not to small KM angles).

The first unambiguous signal for top quarks may come from measurements of R in e^+e^- annihilation. The value of R is given by [in the modified minimal-subtraction ($\overline{\text{MS}}$) scheme]

$$R = 3\sum_q e_q{}^2 \left[1 + \frac{\alpha_s}{\pi} + 1.2\frac{\alpha_s{}^2}{\pi^2} + \cdots \right].$$ (2)

At 29 GeV, the experimental value[3] is 3.95 ± 0.08, whereas the tree-level value is 3.67. The first-order QCD correction is thus certainly detectable (although not very useful for measuring α_s). A large Yukawa coupling will add an additional contribution; if the coupling is as large as α_s, this could compete with the observable QCD correction.[2] We now consider the magnitude of this effect; writing the Yukawa coupling as Ag_Y (so A is a measure of the enhancement—for pseudoscalars, for example, it is x/y).

The relevant diagrams are in Fig. 1. A major difference between this calculation and the QCD calculation is the mass of the Higgs boson; diagram (1b) does not contribute until $\sqrt{s} > 2m_t + m_H$; and the value of R will not level off until much higher energies. If the vertex in (1a) is written as

$$\gamma_\rho F_1(q^2) + \frac{i}{2m_t}\sigma_{\rho\nu}q^\nu F_2(q^2)$$ (3)

then the correction to the cross section is given by[4]

$$\sigma = e_q{}^2 \left[\frac{4\pi\alpha^2}{3q^2}\right]\beta G_0(q^2),$$ (4)
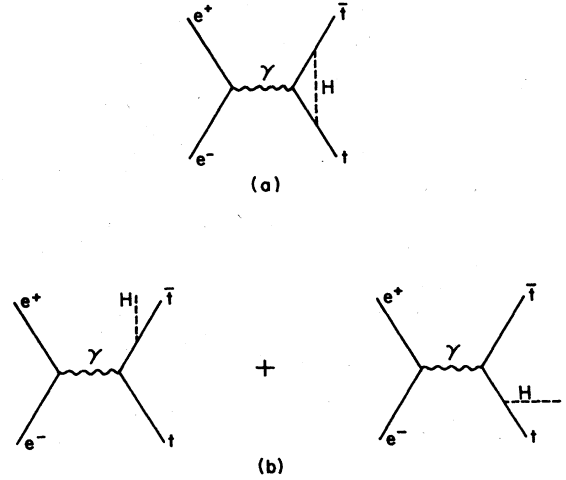
where

(a)

(b)

FIG. 1. Diagrams contributing to the e^+e^- total cross section.

$$G_0(q^2) = F_1\left[1 + \frac{2m_t{}^2}{q^2}\right] + 3F_1F_2 + F_2\left[\frac{q^2}{8m_t{}^2} + 1\right].$$ (5)

We obtain, for $[F_1(q^2) - F_1(0)]$, with $M \equiv m_H/m_t$ and $q \equiv q/m_t$

$$\frac{A^2\alpha_Y}{8\pi}\int_0^1 z\,dz \int_0^1 d\alpha \left[\frac{(2-z)^2 + (q^2+2)z^2\alpha(1-\alpha)}{z^2 + M^2(1-z) - q^2z^2\alpha(1-\alpha)} - \frac{(2-z)^2 + 2z^2\alpha(1-\alpha)}{z^2 + M^2(1-z)} + \ln\left|\frac{z^2 + M^2(1-z) - q^2z^2\alpha(1-\alpha)}{z^2 + M^2(1-z)}\right|\right]$$ (6)

for both the scalar and pseudoscalar exchanges. The charged-Higgs-boson contribution is suppressed by a factor of $m_b{}^2/m_t{}^2$. The contribution for F_2 is

$$\frac{A^2\alpha_Y}{2\pi}\int_0^1 dz\,z^2(2-z)$$

$$\times \int_0^1 d\alpha\frac{1}{z^2 + M^2(1-z) - q^2z^2\alpha(1-\alpha)}.$$ (7)

The contribution of diagram (1b) is zero until $\sqrt{s} > 2m_t + m_H$, and is generally smaller than (1a) (unless the Higgs boson is very light). The total sum of these contributions is plotted in Fig. 2(a) for a scalar and Fig. 2(b) for a pseudoscalar Higgs boson. We have plotted the contribution to R vs s for several values of the Higgs-boson mass, assuming $m_t = 35$ GeV. For different values of m_t, we may use the same noting that the results only depend on $m_H{}^2/m_t{}^2$ and $s/m_t{}^2$. The charged scalar contribution is extremely small.

We see that a measurement of R to a precision of 0.05 would (if no effect were seen) enable bounds to be placed in the A-m_H plane. For $m_H \lesssim 100$ GeV, one sees that the enhancement A could be limited to be less than about 7 (for larger m_t, the bound is more stringent); the result is fairly insensitive to m_H. Thus, measurement of R in e^+e^- annihilation above the $\bar{t}t$ threshold will provide a bound on x/y somewhat tighter than ASW, but sensitive

to neutral-Higgs-boson masses only.

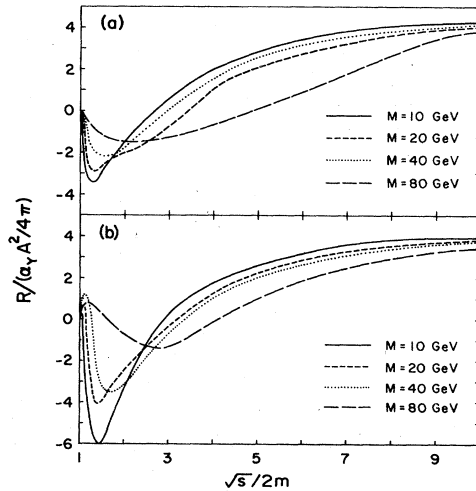We now consider the effects of a large Yukawa coupling on t-quarkonium. In the standard model, the easiest

FIG. 2. Contributions to R due to the diagrams of Fig. 1 where the Higgs boson is a (a) scalar or (b) pseudoscalar. M is the Higgs-boson mass, m is the top-quark mass.

method of seeing the Higgs boson is in quarkonia decays. The rate is[5]

$$\frac{\Gamma(v \to H + \gamma)}{\Gamma(v \to \mu^+ \mu^-)} = \frac{G_F m_v^2}{4\sqrt{2}\,\pi\alpha}\left[1 - \frac{m_H^2}{m_v^2}\right].$$

For a top quark of 45 GeV, and a light Higgs boson, this gives a total branching ratio for $\bar{t}t \to H + \gamma$ of 3%. The Higgs boson then decays into the heaviest quark available. With the monochromatic photon, this process should be fairly easy to detect in the standard model. In two-Higgs-doublet models, it is even easier; the rate is multiplied by A^2. In fact, if the enhancement is large enough, $\bar{t}t \to H + \gamma$ would dominate the decay of t-quarkonium. (If the enhancement were as large as several hundred, the decay would be so rapid that the natural width of the t-quarkonium system would be so large that one could not see it.) Failure to observe the process would enable one to place a limit on A, which is less than 1 if the Higgs boson is light enough. As an example, it has been proposed that the state seen in radiative ψ decays is a Higgs boson; since the rate is too large for the standard model, the two-Higgs-doublet model would be the simplest alternative, in which case A would be determined (see Ref. 6 for a very detailed analysis).

A large Yukawa coupling could also affect the t-quarkonium energy levels. The exchange of a heavy neutral Higgs scalar which is relatively strongly coupled in t-quarkonium should have effects on the t-quarkonium spectra, in particular the splitting of the $2S$ and $1S$ states and the triplet-singlet S-wave splitting. It should also affect the leptonic decay rate which depends on the wave function at the origin. We can examine the dependence of these quantities on the Higgs-boson mass and coupling, which is related to A and to m_t. We understand well the charmonium and b-quarkonium systems using the Schrödinger equation with a well parametrized potential; relativistic effects such as spin-spin splitting are understood using a relativistic two-body equation with a scalar linear confining potential and an asymptotically free vector gluon-exchange potential.[7] Thus we expect to be able to calculate the properties of t-quarkonium, and any drastic departures from these calculations in the S waves could be considered as evidence for a new phenomenon. We will calculate deviations from expected values for t-quarkonium due to the Higgs-boson exchange, and with a fairly conservative definition of a drastic deviation, use them to infer potential bounds on Higgs-boson couplings.

First we examine the $2S$-$1S$ splitting and leptonic decay width with the Schrödinger equation without v^2/c^2 corrections, varying both the coupling $A^2 g_Y^2/4\pi$, m_t, and m_H. The main effect of the short-range Higgs-scalar exchange is to lower the S-wave energy and to pull in the wave function, thus increasing the decay width. It has a much smaller effect on P waves. In order to next evaluate the relativistic equation in this new mass region, we must fix the high-momentum cutoff that arises from inelastic channels becoming predominant. We fix the cutoff by requiring approximately the same $2S$-$1S$ splitting in the relativistic case as in the nonrelativistic case. The result of

this is to take the smooth cutoff parameter equal to the quark mass, which is not very restrictive since the average momentum is of order $p \sim \alpha_c m_t$. With the relativistic equation we can now calculate the triplet-singlet S-wave
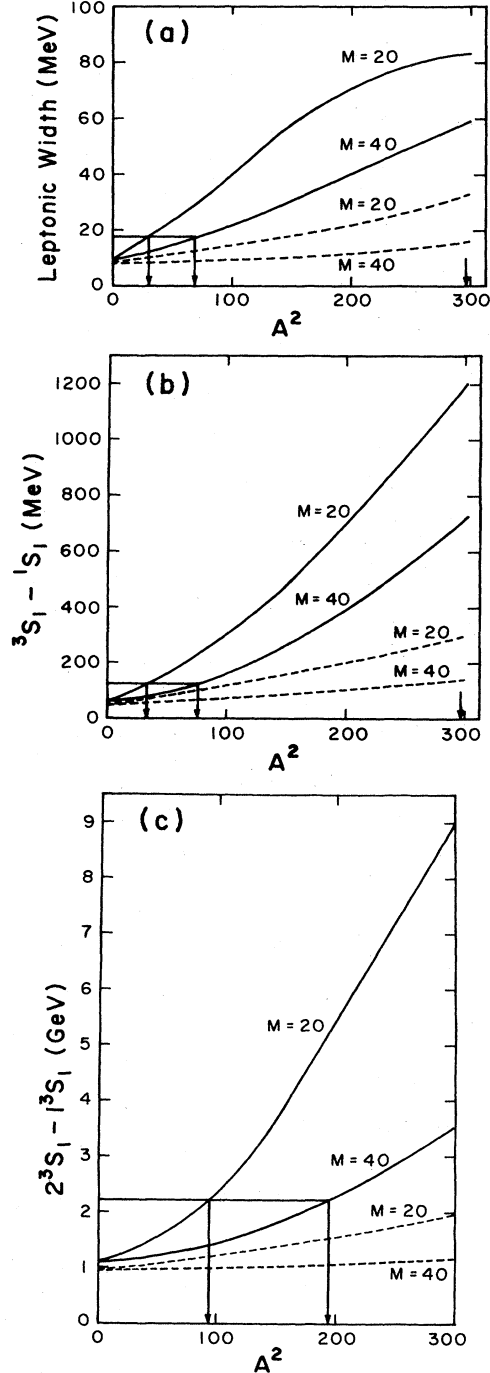

FIG. 3. Contributions of Higgs-scalar exchange to the (a) leptonic width, (b) triplet-singlet splitting, and (c) $2S$-$1S$ splitting for t-quarkonium as a function of the enhancement of the Yukawa coupling. The solid curves are for $m_{top} = 50$ GeV; the dashed curves are for $m_{top} = 35$ GeV. The arrows give the values of the enhancement which yield a factor-of-two discrepancy with pure QCD ($A = 0$).

splittings and the leptonic decay width. Figures 3(a), 3(b), and 3(c) show the results for the $1\,^3S_1$ leptonic decay width, for the $1S$ triplet-singlet splitting and for the $2\,^3S_1$-$1\,^3S_1$ splitting, respectively, all calculated from the relativistic bound-state equations. We see that the leptonic decay width and the triplet-singlet splitting are the most sensitive to the coupling, and that the $2S$-$1S$ splitting is less sensitive. Conservatively using a factor of two in these quantities as evidence of a discrepancy with pure QCD, we have the bounds on the coupling indicated in Figs. 3(a) and 3(b). For the leptonic width or triplet-singlet splitting the bounds (if no discrepancy is seen) for $m_t = 50$ GeV are $A < 6$ for $m_H = 20$ GeV and $A < 9$ for $m_H = 40$ GeV. For $m_t = 25$ GeV, the bounds are much weaker and only give a result for $m_H = 20$ GeV of $A < 16$.

Finally, we consider decays of top quarks. In its conventional weak decay, the top quark (ignoring mixing) decays into a b quark and a virtual W^+, which then converts into a $c + \bar{s}$ (33%), $u + \bar{d}$ (33%), $\tau + \nu$ (11%), $\mu + \nu$ (11%), or $e + \nu$ (11%). Now, however, the charged Higgs boson can mediate the weak decay, and the virtual Higgs boson will convert almost exclusively to $c + \bar{s}$. [We are, assuming the leptons couple to the same Higgs boson as b quarks, as occurs in most models. If this is not true, then some of the virtual Higgs bosons ($\sim 25\%$) convert into $\tau + \nu$, which would change the 3.5 in our final result to 4.1.] The easiest way to detect this would be to look at the fraction of top quarks which decays semileptonically; a value smaller than the standard-model value of 27% (including semileptonic decays of the τ) would be found if the Higgs-boson contribution is significant. Also, an enhancement of $c + \bar{s}$ over $u + \bar{d}$ would be seen.

To estimate this quantitatively, one calculates the decay $t \rightarrow b + (c + \bar{s})$ via both Higgs-boson and W exchange. We find that the ratio of the Higgs-boson to W rates is given by $A^4 m_t^2 m_c^2 / m_H^4$. It is easy to see that this decreases the semileptonic branching ratio by a factor of $(1 + A^4 m_t^2 m_c^2 / 3 m_H^4)$. If the branching ratio can be measured to 10% accuracy, then a value of A as small as $A \sim 2 m_H / 3 (m_t m_c)^{1/2}$ could be detected. Numerically,

for $m_t \sim 35$ GeV, this gives $A \sim 3.5 \; m_H / m_t$; thus finding a standard-model branching ratio would yield a very strong bound on A. This result is also somewhat stronger than ASW, but not dependent on small KM angles.

Thus, a sensitive indicator of an enhancement of the top quark's Yukawa coupling would be (if the charged Higgs boson is not too much heavier than the W) a suppression of the semileptonic decay of the top quark. If the charged Higgs boson is too heavy, then one can look for effects of neutral scalars in the production, decay, energy levels, and leptonic widths of t-quarkonium. If the top quark is discovered in hadron colliders, it will most likely be found through $W \rightarrow t\bar{b}$, in which case detection through semileptonic decays is crucial. The possibility of a suppression of these decays should be kept in mind by top-quark hunters.

Finally, we comment on the limits on A_d. The only limit on A_d previously discussed comes from D^0-$\bar{D}^0$ mixing[1] and from $(g - 2)_\mu$;[2] the limit is very weak ($A_d \lesssim 300$). A stronger limit can be obtained by looking for a suppression of the branching ratio of semileptonic b-quark decays. The argument is similar to the above, although the numbers change somewhat—one replaces $m_t^2 m_c^2$ by $m_b^2 m_s^2$ and must also include phase-space factors. We find that a measurement of the branching ratio to 5% accuracy would allow a limit of $\sim 4 m_H / m_b$ to be set—a considerable improvement over previous bounds. [The current experimental value for the branching ratio of b quarks into electrons is $(11.6 \pm 0.5)\%$, compared with a theoretical value of $(12.5 \pm 0.3)\%$ (Ref. 8). It would, of course, be premature to call this a "suppression" although a 5% discrepancy could, in the future, probably be detected.]

*Present address: University of California, Santa Cruz, California 95064.

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