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t-quarkonium decays into $b\bar{b}$ pairs and charged Higgs bosons

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The process $V_t = {}^3S_1(t\bar{t}) \to b\bar{b}$ is examined as a probe for the effects of virtual charged Higgs bosons $H^{\pm}$, which are present in two-doublet models. The rate and forward-backward asymmetry for this decay are calculated including such effects and explicitly compared to top-quark single-quark decay [especially $t \to b(c\bar{s})$] as a possible testing ground for $H^{\pm}$ masses and couplings.

The expected discovery of t-quarkonium at the new generation of e^+e^- machines (Stanford Linear Collider, LEP at CERN, TRISTAN at KEK), may well be the last achievement of quarkonium physics[1] but it should provide detailed information[2,3] about top-quark weak properties, the quark-antiquark potential at short distances, possible t-quarkonium—Z^0 mixing,[4] and other precision tests of the standard model.[5] Being the heaviest fermion available, it will also likely be the best system to probe the structure of the Higgs sector of the electroweak theory provided, of course, that the Higgs-boson mass(es) is (are) light enough. The Wilczek mechanism[6] for Higgs-boson production, $V_t = {}^3S_1(t\bar{t}) \to H\gamma$, will provide a clean signal and substantial rates for standard-model Higgs-boson masses up to $m_H \lesssim (0.7\text{–}0.9)M_V$ (Ref. 2). Models with two Higgs doublets (as required by supersymmetry) allow for enhanced Yukawa couplings to fermions and for the existence of charged Higgs bosons and tests of these possibilities have also been discussed in the context of t-quarkonium. Three groups[7–9] have investigated the effects of neutral Higgs bosons with enhanced top-quark Yukawa couplings on t-quarkonium energy levels and orderings, leptonic widths, and on the Wilczek decay. As was pointed out some time ago,[10] the existence of a light charged scalar such that $t \to bH^+$ were possible would completely change the pattern of top-quark single-quark decays (SQD's). The contributions of virtual H^+ exchange to the decay $t \to b(c\bar{s})$ would still change the t-quark semileptonic decay branching ratio and could be used to set limits[7] on H^+ masses and couplings. The author of this paper discussed the effects of two Higgs doublets on heavy-quarkonium decays[11] and suggested the process $V_t \to b\bar{b}$ as another probe of virtual charged Higgs bosons. In this note, we reexamine this process, calculating the decay rate (thereby correcting an earlier error), calculating appropriate asymmetries, and explicitly comparing this process to top-quark SQD. (Since the decay $t \to bH^+$ into a real charged Higgs boson would dominate top-quark decays and completely change the character of t-quarkonium, we will assume that $m_{H^+} > m_t - m_b$ in what follows.[12])

In a two-doublet model, the decay rate for $t \to b(c\bar{s})$ via both W and H^+ exchange is given by

$$\Gamma(t \to b(c\bar{s})) = \frac{3G_F{}^2 m_t{}^5}{192\pi^3}\left[f(\rho) + \left[\frac{m_c m_t \cot^2\beta}{2m_H{}^2}\right]^2 g(\sigma)\right], \quad (1)$$

where $\cot\beta = v_1/v_2$ is the ratio of doublet vacuum expectation values, $\rho = (m_t/M_W)^2$, and $\sigma = (m_t/m_H)^2$. The cross term due to W-H interference is negligible and we assume that the weak mixing angle is $|V_{tb}| \simeq 1$. The kinematic factors $f(\rho)$ (Ref. 13) and $g(\sigma)$, which must be taken into account when ρ and σ are non-negligible, are given by

$$\begin{aligned} f(\rho) &= \frac{2}{\rho^4}\{6[\rho + (1-\rho)\ln(1-\rho)] - 3\rho^2 - \rho^3\}, \\ g(\sigma) &= \frac{12}{\sigma^4}\left[(1-\sigma)\left[\frac{1+\sigma}{2} + (3-\sigma)\ln(1-\sigma)\right] - \tfrac{1}{2} + (3-2\sigma)\sigma\right]. \end{aligned} \quad (2)$$

The semileptonic branching ratio of the t (including leptonic decays at the τ) is then given by ($l = e,\mu$)

$$\begin{aligned} B(t \to l\nu_l + \cdots) &= \frac{2.4}{9(1+\epsilon)} \\ &= 0.27(1+\epsilon)^{-1}, \end{aligned} \quad (3)$$

where

$$\epsilon = \frac{1}{3}\left[\frac{m_c m_t \cot^2\beta}{2m_H{}^2}\right]^2 \frac{g(\sigma)}{f(\rho)}.$$

In the range we consider (30 GeV $\le m_t \le$ 60 GeV), the kinematic factor $g(\sigma)/f(\rho)$ can only increase ϵ by a factor of ~ 4. Athanasiu and Gilman[14] have recently examined constraints on $\cot\beta$ and m_H from CP violation in the neutral-K system. If a reasonable fraction of CP violation is due to virtual charged-Higgs-boson exchange, they obtain the bound $\cot\beta \lesssim 2(m_H/m_t)^{1/2}$. (This assumes three generations of fermions; with four generations such stringent constraints might be relaxed.[15]) With this constraint, we find that $\epsilon \lesssim \frac{4}{3}(m_c/m_H)^2 \lesssim 7\times10^{-3}$ (since $m_{H^+} \gtrsim 20$ GeV from e^+e^- production limits). Thus, changes in the top-quark semileptonic branching ratio will be very small if the stringent bounds of Ref. 14 are valid.

The decay $V_t \to b\bar{b}$ has the distinct advantage of being proportional (in amplitude) to $(m_t{}^2 \cot^2\beta / m_H{}^2)$ instead of $(m_c m_t \cot^2\beta / m_H{}^2)$ as in SQD and so can exhibit a much larger effect. Following the notation of Refs. 2 and 3, we find that the amplitude for the reaction $e^-(k)e^+(k') \to b(p)\bar{b}(p')$ via t-quarkonium exchange is

$$\frac{(M_V{}^2 f_V)^2}{S - M_V{}^2 + iM_V\Gamma_V}[\bar{u}(p)\gamma_\mu(\lambda_b - \lambda_b'\gamma_5)v(p')] \times [\bar{v}(k')\gamma_\mu(\lambda_e - \lambda_e'\gamma_5)u(k)] , \tag{4}$$

where

$$\begin{aligned} \lambda_e &= \frac{e^2}{M_V{}^2}\left[e_e e_t + \frac{v_e v_t}{y^2} X_Z \right] , \\ \lambda_e' &= \frac{e^2}{M_V{}^2}\left[\frac{a_e v_t}{y^2} X_Z \right] , \\ \lambda_b &= \frac{e^2}{M_V{}^2}\left[e_b e_t + \frac{v_b v_t}{y^2} X_Z - \frac{1}{6x} X_W - \frac{\cot^2\beta}{12x} X_H \right] , \\ \lambda_b' &= \frac{e^2}{M_V{}^2}\left[\frac{a_b v_t}{y^2} X_Z - \frac{1}{6x} X_W - \frac{\cot^2\beta}{12x} X_H \right] , \end{aligned} \tag{5}$$

where $e_e = -1$, $e_t = \frac{2}{3}$, $e_b = -\frac{1}{3}$, $x = 4\sin^2\theta_W$, $y = 4\sin\theta_W \cos\theta_W$, $v_e = -1 + x$, $v_t = 1 - 2x/3$, $v_b = -1 + x/3$, and $a_e = a_b = -a_t = -1$. Furthermore,

$$\begin{aligned} X_Z &= \frac{M_V{}^2}{M_V{}^2 - M_Z{}^2 + iM_Z\Gamma_Z} , \\ X_W &= \frac{M_V{}^2}{M_W{}^2}\frac{(1 + M_V{}^2/8M_W{}^2)}{(1 + M_V{}^2/4M_W{}^2)} , \\ X_H &= \frac{M_V{}^2}{M_W{}^2}\frac{M_V{}^2}{(M_V{}^2 + 4m_H{}^2)} . \end{aligned} \tag{6}$$

The last two terms in λ_b and λ_b' come from virtual W and H t-channel exchange diagrams upon which a Fierz transformation is applied. (The possibility of γ-Z-W interference in $e^+e^- \to b\bar{b}$ was first discussed in Refs. 16–18.) As is usually done, we assume that $m_t \cos\beta \gg m_b \tan\beta$ in the H^+ exchange diagram.

The decay rate for $V_t \to b\bar{b}$ is then given by

$$R_{b\bar{b}} = \frac{\Gamma(V_t \to b\bar{b})}{\Gamma_0} = \frac{3}{e_t{}^2}\left[\frac{M_V}{e} \right]^4 (|\lambda_b|^2 + |\lambda_b'|^2) , \tag{7}$$

where $\Gamma_0 = \Gamma(V_t \to \gamma^* \to e^+e^-) = 4\pi\alpha^2 e_t{}^2 |\psi(0)|^2 / M_V{}^2$ is the (fictitious) decay rate for $V_t \to e^+e^-$ via a virtual photon only. The definitions of λ_b, λ_b' in Eq. (5) correct an error in Ref. 11 where the Fierz transformation of the W- and H-exchange contributions was done incorrectly. Using Eqs. (5) and (7), we plot in Fig. 1 the fraction of two-jet $b\bar{b}$ final states relative to all two-jet $(q\bar{q})$ decays for a ${}^3S_1(t\bar{t})$ resonance [i.e., $\Gamma(V_t \to b\bar{b}) / \Gamma(V_t \to \sum q\bar{q})$]. Using values of $\cot\beta$ and m_H consistent with the stringent constraints of Ref. 14, we still find that large changes in this ratio are possible. The effects of the H^+-exchange term are, of course, biggest for large M_V and at these values, top-quark weak decays come to dominate the decays of

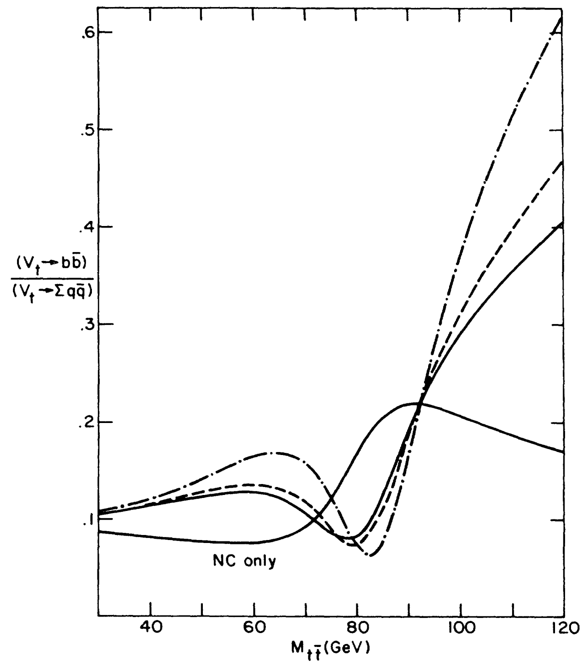

FIG. 1. Fraction of two-jet $b\bar{b}$ pairs among all two-jet decays $(q\bar{q})$ of a ${}^3S_1(t\bar{t})$ resonance [i.e., $\Gamma(V_t \to b\bar{b}) / \Gamma(V_t \to \sum q\bar{q})$] vs M_V. The solid line indicates $\cot\beta = 0$ (i.e., the standard-model prediction), the dashed line indicates $\cot\beta = 1$, $m_H = 60$ GeV, and the dotted-dashed line indicates $\cot\beta = 4$, $m_H = 60$ GeV. The solid curve labeled NC denotes annihilation via the γ and Z^0 channels only, ignoring the effects of W and H exchange, for comparison.

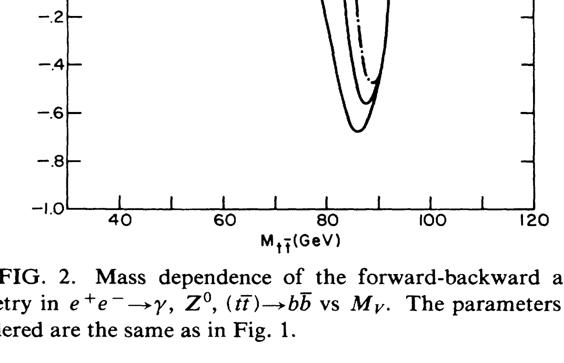

FIG. 2. Mass dependence of the forward-backward asymmetry in $e^+e^- \to \gamma$, Z^0, $(t\bar{t}) \to b\bar{b}$ vs M_V. The parameters considered are the same as in Fig. 1.

t-quarkonia. It should be kept in mind, however, that a light, neutral Higgs boson (with enhanced t-quark Yukawa couplings) will deepen[7,9] the attractive potential well seen by the $t\bar{t}$ pair in a $1S$ state thereby increasing the value of $|\psi(0)|$. Such an effect would enhance all annihilation decays relative to SQD. If identification of $b\bar{b}$ pairs proves possible at such machines (using microvertex detectors[19] for example or distinguishing lepton rich jets) then this process may prove to be the most sensitive way of probing the effects of virtual charged Higgs bosons in the t-quark system. We can also calculate the mass dependence of the forward-backward asymmetry, α_{FB}, in $e^+e^- \rightarrow \gamma, Z, (t\bar{t}) \rightarrow b\bar{b}$ on a ${}^3S_1(t\bar{t})$ resonance including the effects of H^+ exchange and we plot this in Fig. 2. The effects on α_{FB} at higher masses are less dramatic because both W and H exchange yield an effective $V-A$ interaction and so give the same asymmetry. The changes are mostly in the $(\gamma+Z)$ versus $(W+H)$ interference region. (In both figures, the curves labeled NC indicate the effects of ignoring *H and W* exchange for comparison.)

Because of the short t-quark lifetime, T^0-$\bar{T}^0$ and T_c^0-$\bar{T}_c^0$ mixing are expected to be small[20] and may likely not be a useful source of information on charged-Higgs-boson masses and coupling so their effects on the production of $b\bar{b}$ final states in t-quarkonium decay may prove the most useful probe of such properties provided efficient detection of such pairs becomes possible.

As a final comment, we might consider the contributions of the t-channel exchange of other exotic particles to t-quarkonium two-fermion annihilation decays. The excited W's present in many composite[21] models and in the strongly coupled standard model[22] are an example. In addition, the idea of technicolor has undergone something of a modest theoretical[23] and phenomenological[24] revival and one could image the exchange of leptoquark bosons, Δ_{ql}, to such processes as ${}^3S_1 \rightarrow \tau^+\tau^-$ [via $\Delta(Q=-\frac{1}{3})$ exchange with γ, Z, and Δ interference] or ${}^3S_1(t\bar{t}) \rightarrow \upsilon_\tau \bar{\upsilon}_\tau$ [via $\Delta(Q=+\frac{2}{3})$ exchange with Z and Δ interference]. If the couplings of such objects are mass dependent, their effect would be more readily observable in such a system. Moreover, with the canonical value[25] of $M_\Delta \simeq 160$ GeV (or perhaps even lighter[26]), such contributions would give very similar results to some of the cases considered here. (For the prospects of observing such a boson in ep collisions, see Ref. 27.)

Note added in proof. The forward-backward asymmetry in $e^+e^- \rightarrow b\bar{b}$ on the continuum has recently been measured by the JADE Collaboration at DESY PETRA (Ref. 28) by tagging the b quarks via muons from their semileptonic decays. Similar techniques may be useful for probing the asymmetry in $e^+e^- \rightarrow V_t \rightarrow b\bar{b}$ discussed above at higher energies.

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