Extra Z's from E_6 and other exotic physics in heavy-quarkonium decays

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We examine the sensitivity of various asymmetries for the process $e^+e^-\to\mu^+\mu^-$ on top of a $V_Q={}^3S_1(Q\bar{Q})$ resonance to the presence of a new, heavy neutral boson $Z(\Theta)$, present in many superstring-inspired models based on E_6. We also consider the possible effects of light $(M<G_F{}^{-1/2})$ leptoquark bosons on $V_t\to\nu_\tau\bar{\nu}_\tau,\tau^+\tau^-$.

I. INTRODUCTION

The hoped-for discovery of t-quarkonium[1–4] at the Stanford Linear Collider (SLC) or LEP at CERN (or perhaps TRISTAN at KEK) would not only provide a laboratory for the study of the properties of the top quark and the $Q\bar{Q}$ potential at short distances but for the observation of other important standard-model processes as well. Precision electroweak tests on t-quarkonium have been discussed[5] and will likely be measurable for any accessible $M(V_t)$ [where $V_Q={}^3S_1(Q\bar{Q})$] whereas such processes as $V_t\to H^0\gamma$ (Ref. 6) and V_t-Z^0 mixing[7] will depend on the masses of the V_t, Z^0, and Higgs boson H^0. t-quarkonium can also be used to probe physics beyond the standard model and tests for supersymmetry,[2,8] technicolor,[2] and the extra Higgs bosons (both neutral[9,10] and charged[10,11]) present in the two-Higgs-doublet models required by supersymmetry have been proposed. In this paper, we discuss two additional kinds of new physics which could affect the decays and asymmetries measured on a heavy V_Q resonance. We will consider not only V_t but also $V_{b'}$ where b' is a fourth-generation, $Q=-\frac{1}{3}$ isodoublet quark, and V_h, with h an exotic, $Q=-\frac{1}{3}$ isosinglet quark present in the 27 of E_6 (Ref. 12). This last case is motivated by the discussion in Sec. II where we examine the forward-backward asymmetry (A_{FB}) and left-right asymmetry (A_{LR}) in $e^+e^-\to\mu^+\mu^-$ on top of such resonances and their sensitivities to the presence of an extra Z boson present in extended [extra U(1)] electroweak models based on superstring-inspired E_6 theories. Finally, in Sec. III, we consider the effects of the t-channel exchange of leptoquark bosons $\chi(+\frac{2}{3})$, $\chi(-\frac{1}{3})$ on the annihilation decays $V_t\to\nu_\tau\bar{\nu}_\tau,\tau^+\tau^-$.

II. NEW Z's FROM E_6 AND HEAVY QUARKONIA

Inspired by the suggestion that superstring theories[13] based on $E_8\times E_8'$ may give a consistent and finite theory of gravitation, the observed gauge interactions, and matter, there has been a revival of interest in the study of extended electroweak theories based on $SU(2)_L\times U(1)_Y\times U(1)_\Theta$ derived from E_6 and the phenomenology of the resulting additional Z boson.[14,15] In this notation, the new boson is $Z(\Theta)=\cos\Theta\, Z_\psi+\sin\Theta\, Z_\chi$ where $E_6\to SO(10)\times U(1)_\psi$ and $SO(10)\to SU(5)\times U(1)_\chi$. (See Ref. 14 for details.) Limits on the mass of such a new $Z(\Theta)$ have been derived,[16,17] using low-energy neutral-current data, direct searches for a second Z' in UA1/UA2 collider data, and from electroweak radiative corrections.[18] Such limits are Θ dependent but they typically require that $M(Z(\Theta))\geq 150$–225 GeV. Prospects for the observation and/or production of the $Z(\Theta)$ in $pp/p\bar{p}$ (Refs. 17 and 19), e^+e^- (Refs. 20 and 21), and ep (Refs 21 and 22) collisions have also been discussed. Many authors[20] have argued that deviations in various asymmetries in $e^+e^-\to\mu^+\mu^-$, either the forward-backward asymmetry (A_{FB}) or the left-right asymmetry (A_{LR}) (assuming the possibility of a polarized electron beam as at SLC), from standard-model predictions (including radiative corrections[23]) could indicate the presence of such a new Z in a mass range well beyond that directly accessible (>100 GeV). As is well known,[2,24] these asymmetries are very different when measured on top of a ${}^3S_1(Q\bar{Q})$ resonance than on the continuum or Z^0 pole (as is seen in Fig. 1) and in this section we wish to examine the sensitivity of such deviations on top of various V_Q resonances to the existence of a $Z(\Theta)$.

If we assume that the $U(1)_\psi$ and the $U(1)_\chi$ gauge groups are characterized by the same coupling constant as the (properly normalized) $U(1)_Y$ factor, as they would be if $E_6\to SU(3)\times SU(2)\times U(1)_Y\times U(1)_\psi\times U(1)_\chi$ all at once (at least up to possible superstring corrections[25]), then we have $g=\sqrt{\frac{5}{3}}e/\cos\theta_W$. The vector and axial-vector couplings necessary to calculate A_{FB} and A_{LR}, including the effects of the $Z(\Theta)$, are then

$$\lambda_f=e_fe_Q+\frac{v_fv_Q}{y^2}\chi_Z+\frac{5}{3}\frac{v_f'v_Q'}{\cos^2\theta_W}\chi_Z' ,$$
$$\lambda_f'=\frac{a_fv_Q}{y^2}\chi_Z+\frac{5}{3}\frac{a_f'v_Q'}{\cos^2\theta_W}\chi_Z' , \tag{2.1}$$

where

$$v_f=2(I_{3L}+I_{3R})_f-4e_f\sin^2\theta_W ,$$
$$a_f=2(I_{3L}+I_{3R})_f ,$$
$$y=4\sin\theta_W\cos\theta_W ,$$
$$\chi_Z=\frac{M^2}{M^2-M_Z{}^2+iM_Z\Gamma_Z} ,$$

and $M=M(V_Q)$ with a similar expression for χ_Z'. The

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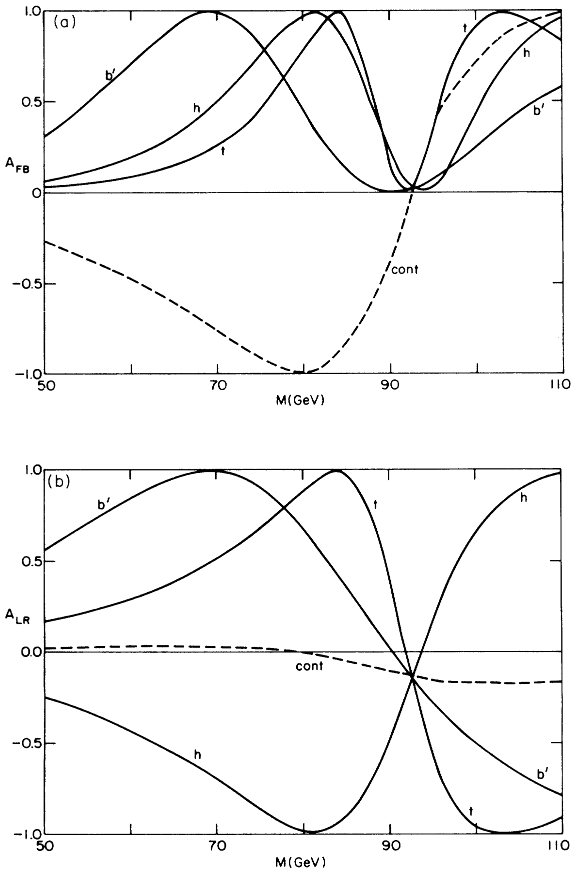

FIG. 1. (a) The forward-backward asymmetry A_{FB} in $e^+e^-\to\mu^+\mu^-$ on top of various $V_Q={}^3S_1(Q\bar{Q})$ resonances as a function of the mass $M(V_Q)$ (solid curves). Curves are plotted for the top quark, t, b' (a fourth-generation sequential $Q=-\frac{1}{3}$ quark), and for h ($aQ=-\frac{1}{3}$ "exotic," isosinglet quark from an E_6 27-plet). The dashed curve is the value of A_{FB} on the continuum for comparison. (b) Same as (a) but for the left-right symmetry A_{LR}.

left-right asymmetry in $e^+e^-\to\mu^+\mu^-$ on a V_Q resonance, defined as $(\sigma_R-\sigma_L)/(\sigma_L+\sigma_R)$, is then

$$A_{LR}=-2\frac{\mathrm{Re}(\lambda_e^*\lambda_e)}{|\lambda_e|^2+|\lambda_e'|^2} \tag{2.2}$$

while the forward-backward asymmetry, defined from

$$\frac{dN}{d\cos\theta}\propto 1+\cos^2\theta+2A_{FB}\cos\theta\ , \tag{2.3}$$

leading to $(N_F-N_B)/(N_F+N_B)=\frac{3}{4}A_{LR}$, is given by[2,24]

$$A_{FB}=(A_{LR})^2\ . \tag{2.4}$$

In what follows, we assume, for simplicity, no Z^0-$Z(\theta)$ mixing[20] and use $M_Z=92.5$ GeV, $\Gamma_Z=2.8$ GeV, and $\sin^2\theta_W=0.232$. We further assume that the $Z(\Theta)$ can decay into three generations of ordinary fermions only and not into any of the exotic fermions in the E_6 27-plet but our results are, however, almost completely insensitive to the exact value of the $Z(\Theta)$ width. The vector (v_f') and axial-vector (a_f') couplings of the fermions of interest to the $Z(\Theta)$ can be derived from Ref. 14 where the charges for all the left-handed states in the **27** are given by using $v_f'=(Q_L-\bar{Q}_L)/2$, $a_f'=(Q_L+\bar{Q}_L)/2$ and we find the values given in Table I. [We assume a coupling of the form $g\gamma_\mu(v_f'-a_f'\gamma_5)$ (Ref. 26).] The most important thing to note is that because both the u_L and $\bar{u}_L$ are in the same SU(5) representation (and hence have the same χ and Ψ charges) then the t-quark–$Z(\Theta)$ vector coupling v_t' vanishes identically, implying that a new Z, at least in the context of superstring-motivated models, will have *no* effect on either asymmetry for t-quarkonium. In addition, if $\sin\Theta=0$ [i.e., if $Z(\Theta)=Z_\Psi$] then *no* heavy quarkonium will be useful for probing the effects of the $Z(\Theta)$ since then both $v'(b')$ and $v'(h)$ vanish. Keeping this in mind, we can calculate the deviations in A_{FB} and A_{LR} for $V_{b'}$ and V_h quarkonia due to various $Z(\Theta)$ for $\sin\Theta\neq 0$. Examples of such deviations are plotted in Figs. 2 and 3. [In Fig. 2, we have assumed that $\sin\Theta=1.0$ while in Fig. 3 we have used $\Theta=\arctan(\sqrt{\frac{3}{5}})$, which is the specified value if the E_6 group is broken to a rank-5 group.[27]] For comparison, the deviations in A_{LR} and A_{FB} on the continuum are also plotted. For these cases, we use the definitions

$$F(h_f,h_e)=e_fe_e+\frac{(v_f-h_fa_f)(v_e-h_ea_e)}{y^2}X_z+\frac{5}{3}\frac{(v_f'-h_fa_f')(v_e'-h_ea_e')}{\cos^2\theta_W}X_Z'\ ,$$

$$A_{LR}(\mathrm{cont})=\frac{\sum_{h_f,h_e}h_e|F(h_f,h_e)|^2}{\sum_{h_f,h_e}|F(h_f,h_e)|^2}\ , \tag{2.5}$$

$$A_{FB}(\mathrm{cont})=\frac{\sum_{h_f,h_e}h_fh_e|F(h_f,h_e)|^2}{\sum_{h_f,h_e}|F(h_f,h_e)|^2}\ ,$$

where h_e,h_f are the fermion helicities.

We see that it is possible in certain cases to have much larger *deviations* in both A_{FB} and A_{LR} on top of a b'- or h-quarkonium state than on the continuum or Z^0 pole but several other factors must also be considered. The asymmetry which is actually measured[2,3] on such resonance is

$$\langle A\rangle=(A^{\mathrm{on}}+\eta A^{\mathrm{off}})/(1+\eta)\ ,$$

where $\eta=R(\mathrm{continuum})/R(\mathrm{resonance})$ (which parametrizes the "contamination" due to the continuum back-

TABLE I. Values of vector and axial-vector couplings of fermions to $Z(\Theta)$. [The interaction is defined by $g_\Theta\bar{f}\gamma_\mu(v_f'-a_f'\gamma_5)fZ_\mu(\Theta)$.]

e	$\sin\Theta/\sqrt{10}$	$-\cos\Theta/2\sqrt{6}+\sin\Theta/2\sqrt{10}$
u	0	$-\cos\Theta/2\sqrt{6}-\sin\Theta/2\sqrt{10}$
d	$-\sin\Theta/\sqrt{10}$	$-\cos\Theta/2\sqrt{6}+\sin\Theta/2\sqrt{10}$
h	$\sin\Theta/\sqrt{10}$	$\cos\Theta/\sqrt{6}$

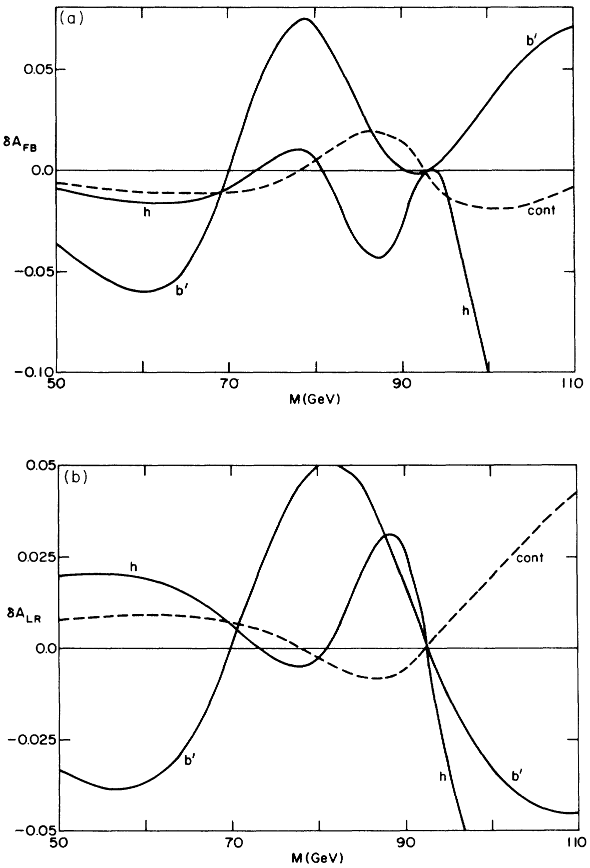

FIG. 2. (a) The *deviation* in A_{FB} in $e^+e^-\to\mu^+\mu^-$ due to the presence of a $Z(\Theta)$ with $M(Z(\Theta))=250$ GeV and $\sin\Theta=1$. (b) Same as (a) but for the deviation in A_{LR}.

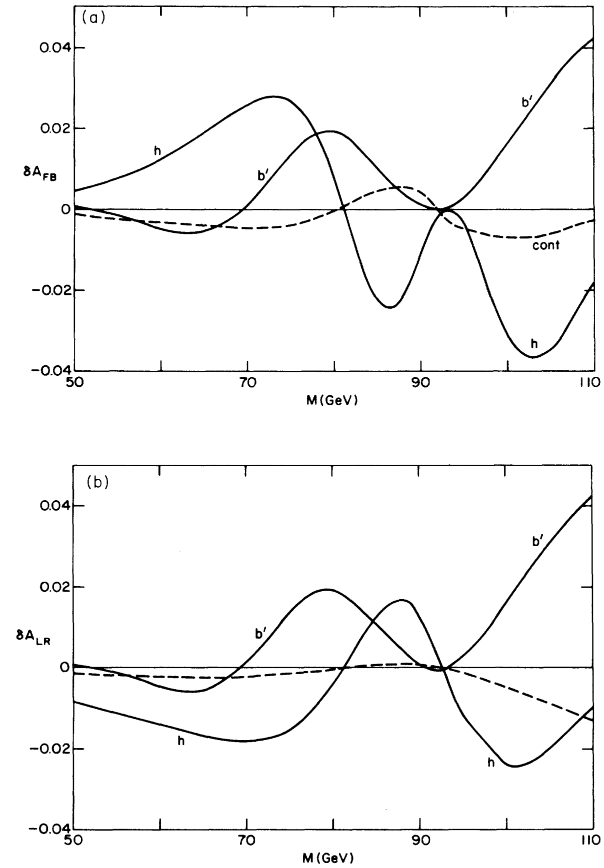

FIG. 3. (a) The deviation in A_{FB} for $M(Z(\Theta))=250$ GeV and $\Theta=\arctan(\sqrt{3/5})$. (b) The deviation in A_{LR} for $M(Z(\Theta))=250$ GeV and $\Theta=\arctan(\sqrt{3/5})$.

ground) depends sensitively on the V_Q mass and decay properties. In addition, the effects of averaging over the beam energy profile[2,3] will also lower the "analyzing power" of such deviation measurements. Also, a large statistical sample can be observed on the Z^0 pole while any quarkonium resonance will inevitably yield a more limited rate (but still large compared to the continuum). A detailed analysis of all such effects is beyond the scope of this paper, but we can still argue that for a reasonably large range of new quarkonium parameters the search for deviations in the asymmetries we have discussed can be roughly competitive with (or at the very least, complementary to) the planned searches on the Z^0 pole.

Two additional comments concerning such new quarkonia are perhaps in order. The decay rate for a heavy t-quarkonium state (say $m_t > 55$ GeV) is dominated by the single-quark weak decay of the top quark itself so that many possible new physics signals would be washed out by its large decay width. Fourth-generation b'- and h-quarkonia are expected to have such weak decays highly suppressed and the more traditional annihilation decay modes should dominate. For the b' this is possible because one expects that $m_b' < m_t'$ (and perhaps lighter than m_t as well) so that its weak decays are suppressed by small Kobayashi-Maskawa mixing angles (and perhaps phase space). The h quarks, being isosinglets, only decay weakly via their (unknown) mixing with the usual d-type quarks and this may also be small in order to satisfy constraints from flavor-changing neutral-current phenomenology.[28-30] If an extra $Z(\Theta)$ from string-inspired E_6 models does indeed appear at relatively low energies ($\lesssim 1$ TeV), then it must be accompanied by the additional exotic fermions in the E_6 27-plet if for no other reason than to cancel anomalies.[31] Thus it is natural (perhaps unavoidable) to consider "exotic" h-quarkonia if one is discussing the $Z(\Theta)$. If both the $Z(\Theta)$and the h quarks, both isosinglets, acquire their masses through coupling to a common isosinglet Higgs boson,[32] as is expected in superstring models, then unitarity and renormalization-group arguments imply that the h quarks cannot be more than a factor of (α_s/α_w) heavier than the $Z(\Theta)$ and could, of course, be much lighter.

III. LEPTOQUARK BOSONS AND t-QUARKONIUM

The t-quarkonium system, and other heavy quarkonia, are ideal places to look for the effects of new particles with mass-dependent couplings. The standard-model

Higgs boson, if light enough, will be copiously produced in radiative V_t decays as long as $M_H < (0.7\text{–}0.9)M(V_t)$ (Ref. 2) while nonstandard Higgs bosons can also exhibit dramatic effects.[9–11] The author of Ref. 11 has stressed that the t-channel exchange of a charged Higgs boson can dramatically affect the standard-model predictions for the rate and forward-backward asymmetry for $e^+e^- \to V_t \to b\bar{b}$ where there is already an interesting γ-Z^0-W interference effect.[24] (This asymmetry in $e^+e^- \to \bar{b}b$ has already been observed on the continuum at the DESY storage ring PETRA at lower energies by tagging b quarks via their decay muons.[33])

With this in mind, we will consider the possibility that light leptoquark bosons with mass-dependent couplings could similarly affect other such annihilation decays or asymmetries. Leptoquark gauge bosons [as in the SU(4) group of Pati and Salam[34]] with standard gauge couplings have strong constraints on their masses[35,36] from analyses of rare decay processes, typically $M > 1\text{–}100$ TeV. If such group factors are embedded in a grand unified theory [say SO(10), with or without supersymmetry], then renormalization-group arguments[36] imply that $M > 10^{10}\text{–}10^{12}$ GeV. However, several authors have considered the possibility of light ($M < G_F^{-1/2} \simeq 250$ GeV) leptoquark bosons in the context of left-right-symmetric models[37] where they appear as necessary Higgs bosons or in SU(5)-type models.[38] As an example of such a possibility, we will consider the explicit model of Ref. 39 where the authors discuss $Q = +\frac{2}{3}$, isosinglet leptoquark (spin-zero) bosons χ_i, one per generation ($i = 1,2,3$), as suggested by the model of "nearby compositeness" that they consider. With Goldstone-boson-like, mass-dependent couplings given by

$$\frac{Ag_W}{2M_W}\bar{q}[m_q(1+\gamma_5) - m_l(1-\gamma_5)]l\chi + \text{H.c.} , \tag{3.1}$$

these bosons are consistent with limits from rare decays for $(A/1.0) < (M/100 \text{ GeV})$ while a residual U(1) symmetry solves possible problems with proton decay. Furthermore, the masses of such states are argued to satisfy $M < (\alpha_s/\pi)^{1/2} G_F^{-1/2} \lesssim 100$ GeV. Such leptoquark bosons have been looked for in e^+e^- collisions with the resulting limit[40] $M > 20.5$ GeV. This would still allow them to be produced in Z^0 decays with a rate

$$\frac{\Gamma(Z^0 \to \chi_i \chi_i^*)}{\Gamma(Z^0 \to \nu_e \bar{\nu}_e)} = \frac{8}{3}\frac{\sin^4\Theta_W}{\cos^2\Theta_W}\left[1 - \frac{4M_\chi^2}{M_Z^2}\right]^{3/2} , \tag{3.2}$$

but limits on their mass which are, in principle, derivable from UA1/UA2 collider data will likely preclude such decays. Since the χ_i are color-triplet, spin-zero bosons, they can be pair-produced via gluon fusion in $p\bar{p}$ collisions in much the same way as the scalar quarks of supersymmetry. Moreover, the first generation χ_1, for example, will have $B(\chi_1 \to u\bar{\nu}_e) = 0.25$ and so will have a similar decay signature to that of scalar quarks, $\tilde{q} \to q\tilde{\gamma}$, i.e., a jet plus missing transverse energy or p_T. Thus, the analyses of monojet/dijet events[41] with missing E_T which are used to limit $M_{\tilde{q}}$ can also be applied to leptoquarks (at least χ_1) to give $M_\chi > 40\text{–}50$ GeV. Similar or stronger limits from analyses of $p\bar{p} \to$ jet + jet + l^+l^- events will likely only increase this bound. If light enough, the χ_3 could certainly appear directly in t-quark decays, $t \to \chi_3 \nu_\tau$ but the limits above may make this unlikely as well so we are naturally led to consider its virtual effects in heavy-quarkonium systems. Just as with charged Higgs bosons,[10,11] such a χ_3 could contribute virtually to certain t decay modes, in this case $t \to \nu_\tau(b\tau^+)$ and hence could affect the top-quark semileptonic branching ratio, $B(t \to l + \cdots)$ where $l = e,\mu$. With values of A and M consistent with the rare decay bounds discussed above, however, this branching ratio will change by less than 1% due to such a χ_3. Thus, we are led to examine its t-channel exchange contribution to the decay $V_t \to \nu_\tau\bar{\nu}_\tau$. Motivated by the suggestion that neutrino counting on V_Q states may be useful,[42] we calculate $\Delta\Gamma/\Gamma$ due to the presence of a χ_3 with $M = 80$ GeV and $A = 0.8$ which we plot in Fig. 4 as an example. Because it is also argued that such neutrino-counting experiments may be more efficient on a fourth-generation b' vector resonance, we also plot $\Delta\Gamma/\Gamma$ for $V_b' \to \nu_\tau'\bar{\nu}_\tau'$ where ν_τ' is a (massless) fourth-generation neutrino. (Limits on fourth-generation neutrinos from big-bang nucleosynthesis and neutrino-counting experiments at colliders are still compatible with $N_\nu = 4$.) We see that in neither case is the possible deviation likely large enough to be measured given the expected sensitivity of such experiments. As a final comment, we might also consider $Q = -\frac{1}{3}$ leptoquarks which couple to, e.g., $t\tau^-$ [with a similar coupling to Eq. (3.1) but with appropriate charge-conjugate spinors] such as are considered in Ref. 37. These could have an effect on $V_t \to \tau^+\tau^-$ and hence on A_{FB} and A_{LR} for this process which is often used to check for universality and to increase the statistical power of an experiment by combining with the $\mu^-\mu^+$ data. The deviations in A_{FB} and A_{LR} due to a similarly coupled leptoquark boson ($A = 0.8, M = 80$ GeV) can be as large as 0.04 and so this possibility should also be kept in mind. (The idea that new physics, namely, compositeness, might affect the asymmetries in $e^+e^- \to \tau^+\tau^-$ on t-quarkonium have been discussed recently[43] but in a different context.)

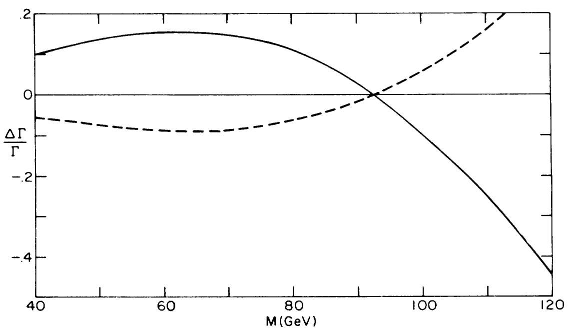

FIG. 4. The fractional change in the decay rate for $V_t \to \nu_\tau\nu_\tau$ due to a $Q = +\frac{2}{3}$ leptoquark boson with $M = 80$ GeV and $A = 0.8$ (solid curve). The dashed curve is the deviation for $V_{b'} \to \nu_\tau'\bar{\nu}_\tau'$ for the same boson.

[1]E. Eichten, in *The Sixth Quark,* proceedings of the 12th SLAC Summer Institute on Particle Physics, Stanford, 1984, edited by P. McDonough (SLAC Report No. 281, 1984), p. 1.
[2]W. Buchmüller *et al.*, in *Physics at LEP,* proceedings of the LEP Physics Jamboree, Geneva, Switzerland, 1985, edited by J. Ellis and R. Peccei (CERN Report No. 86-02, 1986), Vol. 1, p. 203.
[3]S. Güsken, J. H. Kühn, and P. M. Zerwas, Nucl. Phys. **B262**, 393 (1985).
[4]I. Dremin, Usp. Fiz. Nauk **150**, 185 (1986).
[5]B. Grzadkowski, P. Krawczyk, J. H. Kühn, and R. G. Stewart, Phys. Lett. **63B**, 247 (1985); **176B**, 456 (1986); Nucl. Phys. **B281**, 18 (1987).
[6]F. Wilczek, Phys. Rev. Lett. **39**, 1304 (1977); P. Nason, Phys. Lett. **175B**, 223 (1986).
[7]J. H. Kühn and P. M. Zerwas, Phys. Lett. **154B**, 448 (1985); P. J. Franzini and F. Gilman, Phys. Rev. D **32**, 237 (1985); L. J. Hall, S. King, and S. Sharpe, Nucl. Phys. **B260**, 510 (1985).
[8]J. Ellis and S. Rudaz, Phys. Lett. **128B**, 248 (1983); J. H. Kuhn, Acta Phys. Pol. **B16**, 969 (1985).
[9]M. Chaichian and M. Hayashi, Phys. Rev. D **32**, 144 (1985); G. Athanasiu, P. J. Franzini, and F. Gilman, *ibid.* **32**, 3010 (1985); L. Bergström and P. Poutiainen, Phys. Lett. **182B**, 83 (1986).
[10]M. Sher and D. Silverman, Phys. Rev. D **31**, 95 (1985).
[11]R. W. Robinett, Phys. Rev. D **31**, 736 (1986); **35**, 2897 (1987).
[12]For a recent discussion of such b'- and h-quarkonia, see J. Hewett and T. G. Rizzo, Phys. Rev. D **35**, 2194 (1987). For a discussion of superheavy fourth-generation b'-quarkonia in a different context, see V. Barger *et al.*, *ibid.* **35**, 3366 (1987).
[13]M. B. Green, J. Schwarz, and E. Witten, *Superstring Theory* (Cambridge University Press, Cambridge, England, 1987).
[14]D. London and J. L. Rosner, Phys. Rev. D **34**, 1530 (1986).
[15]E. Cohen, J. Ellis, K. Enqvist, and D. Nanopoulos, Phys. Lett. **161B**, 85 (1985); V. Barger, N. Deshpande, and K. Whisnant, Phys. Rev. Lett. **56**, 30 (1986); Phys. Rev. D **35**, 1005 (1987); J. Ellis, K. Enqvist, D. Nanopoulos, and F. Zwirner, Mod. Phys. Lett. **A1**, 57 (1986).
[16]L. Durkin and P. Langacker, Phys. Lett. **166B**, 436 (1986); F. del Aguila, G. Blair, M. Daniel, and G. G. Ross, Nucl. Phys. **B283**, 50 (1987).
[17]V. Barger, N. Deshpande, J. L. Rosner, and K. Whisnant, Phys. Rev. D **35**, 2893 (1987).
[18]W. J. Marciano, and A. Sirlin, Phys. Rev. D **35**, 1672 (1987).
[19]P. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. D **30**, 1470 (1984).
[20]M. Cvetič and B. W. Lynn, Phys. Rev. D **35**, 51 (1986); F. del Aguila, M. Quirós, and F. Zwirner, Nucl. Phys. **B284**, 530 (1987); G. Bélanger and S. Godfrey, Phys. Rev. D **34**, 1309 (1986); **35**, 378 (1987); D. London, G. Bélanger, and J. Ng, Phys. Rev. Lett. **58**, 6 (1987); P. Franzini and F. Gilman, Phys. Rev. D **35**, 855 (1987); J. P. Ader, S. Narison, and J. C. Wallet, Phys. Lett. **173B**, 215 (1986).
[21]V. D. Angelopoulos, J. Ellis, and D. Nanopoulos, Phys. Lett. **176B**, 703 (1986).
[22]F. Cornet and R. Rückl, Phys. Lett. **184B**, 263 (1987).
[23]G. Altarelli *et al.*, in *Physics at LEP* (Ref. 2), p. 1.
[24]L. M. Shegal and P. M. Zerwas, Nucl. Phys. **B183**, 417 (1981).
[25]K. Choi and J. E. Kim, Phys. Lett. **165B**, 71 (1985).
[26]The values in Table I agree with those of Bélanger and Godfrey (Ref. 20) if $\Theta \rightarrow \Theta + \pi/2$.
[27]See, e.g., Ref. 14 and references therein. See also Cohen *et al.* (Ref. 15) and P. Binétruy *et al.*, Nucl. Phys. **B273**, 50 (1986).
[28]S. M. Barr, Phys. Rev. Lett. **55**, 2778 (1985).
[29]R. Robinett, Phys. Rev. D **33**, 1908 (1986).
[30]V. Barger, N. Deshpande, R. J. N. Phillips, and K. Whisnant, Phys. Rev. D **33**, 1912 (1986).
[31]S. M. Barr, B. Bednarz, and C. Benesh, Phys. Rev. D **34**, 155 (1986).
[32]R. Robinett, Phys. Rev. D **34**, 182 (1986).
[33]B. Naroska, Phys. Rep. **148**, 67 (1987).
[34]J. C. Pati and A. Salem, Phys. Rev. Lett. **31**, 661 (1973).
[35]O. Shankar, Nucl. Phys. **B206**, 253 (1982).
[36]R. Robinett, Phys. Lett. **116B**, 144 (1982).
[37]R. N. Mohapatra, G. Segrè, and L. Wolfenstein, Phys. Lett. **145B**, 433 (1984).
[38]W. Buchmüller and D. Wyler, Phys. Lett. **177B**, 377 (1986).
[39]B. Schrempp and F. Schrempp, Phys. Lett. **153B**, 101 (1985).
[40]CELLO Collaboration, H. Behrend *et al.*, Phys. Lett. **173B**, 452 (1986).
[41]See, e.g., R. M. Barnett, H. E. Haber, and G. L. Kane, Nucl. Phys. **B267**, 625 (1986).
[42]L. Krauss and F. Wilczek, Phys. Lett. **181B**, 380 (1986).
[43]J. Pati and H. Stremnitzer, Phys. Rev. Lett. **56**, 2152 (1986).