

## TOPONIUM AND TWO-HIGGS MODELS\*

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### ABSTRACT

Bounds from  $B^0 - \bar{B}^0$  mixing on charged-Higgs-boson masses and couplings in two-Higgs-doublet models are presented. These bounds are comparable to those obtained, with additional assumptions, from the neutral- $K$ -system. The effects of the neutral Higgs bosons of these models on the spectrum and wave function of toponium is discussed. These effects could, in the future, lead to limits on, or the discovery of, these Higgs bosons.

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## 1. Introduction

The Higgs sector remains the most elusive (and to some, unsatisfactory) feature of the standard model. It has often been suggested that it should be enlarged, or replaced altogether by bound states dynamically generated by a new strong interaction.<sup>[1]</sup> Staying within “conventional” Higgs structures, there is no reason not to consider multiple Higgs doublets. In fact, many currently interesting theories, such as SUSY, left-right symmetric models, and superstring theories, require more than one doublet. Moreover, extra doublets can “decouple” the CP violation parameters  $\epsilon$  and  $\epsilon'$ , which could prove useful if, with future measurements, the standard model is unable to account simultaneously for both values.

I will consider models with two Higgs doublets, although much of what I will discuss can be generalized to include more doublets. The new particles are two charged and two neutral bosons; an additional parameter is the vacuum expectation value (VEV) of the new doublet—or, equivalently, the ratio of the VEV’s of the two doublets, if we fix an appropriate combination to be that of the standard model. Changing this VEV ratio changes the strength of the physical Higgs couplings and hence the size of the effects of the additional bosons; current physics, through the experimental absence of these effects, places limits on allowable values of the VEV ratio.

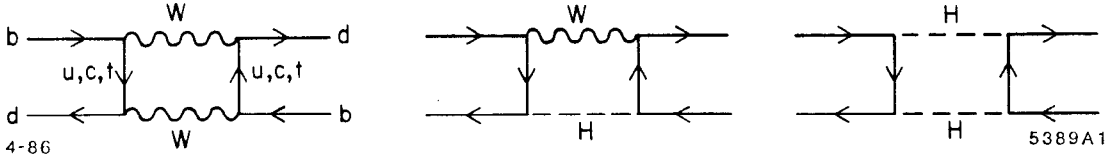
One first requires that flavor-changing neutral currents (FCNC) be absent at tree level. This can be done by imposing a discrete symmetry that forbids certain Higgs couplings. One scheme<sup>[2]</sup> requires one Higgs doublet to couple only to up-type quarks (i.e.,  $u$ ,  $c$ , and  $t$ ) and the other only to down-type quarks. Thus, for each set of quarks, a single Higgs doublet is responsible for both mass matrix and neutral Higgs couplings, so, as in the standard model, the two matrices diagonalize simultaneously and FCNC are absent at tree level. Another scheme<sup>[3]</sup> allows only one Higgs doublet to couple to quarks at all, so that again the mass and coupling matrices diagonalize simultaneously.

In this talk I would like to discuss bounds on masses and couplings (VEV ratios) of charged Higgs bosons that follow from their effects on neutral  $B$  meson mixing. I will compare these bounds to those derived from the  $K_S^0 - K_L^0$  difference,<sup>[4]</sup> and to those derived, with additional assumptions, from  $CP$ -violating effects in the  $K$  system.<sup>[5]</sup> I will then consider the effects of neutral-Higgs boson exchange on toponium physics. The Higgs exchange adds an attractive term to the interquark potential, which, for allowed values of the relevant parameters, can have dramatic effects on the spectrum and wave functions of toponium. However, distinguishing these effects from the variations of different, but theoretically acceptable, potentials, can present a problem.

This talk is based on work done with Gregory Athanasiu and Fred Gilman.<sup>[6]</sup>

## 2. Limits from $B^0 - \bar{B}^0$ mixing

There are three box diagrams contributing in lowest order to  $B^0 - \bar{B}^0$  mixing:



The first is the standard model contribution. The other two can only occur in a model with more than one Higgs doublet, as H is the physical, charged Higgs. The  $t$  quark contribution dominates the expression for the mass difference, since it is weighted by Kobayashi-Maskawa (KM) angle factors whose magnitudes are similar to those for the charm quark, while  $m_t^2 \gg m_c^2$ . Thus we expect much tighter bounds than those found in the  $K$ -meson system; additionally, the freedom in choosing matrix elements, and in KM angle related factors is considerably smaller than in the  $K$ -meson system.

CLEO, at the  $e^+e^-$  storage ring CESR, observes  $B_d^0$  and  $\bar{B}_d^0$  mesons pair produced near threshold, *i.e.*, without other particles. Their decay amplitudes are therefore coherent, and the like sign to opposite sign dilepton ratio is equal to the “wrong”-sign lepton to “right”-sign lepton ratio for a single  $B$  meson. This can be written as follows (neglecting effects of possible  $CP$  violation)

$$r = \frac{N(l^+l^+) + N(l^-l^-)}{N(l^+l^-) + N(l^-l^+)} = \frac{\Gamma(B^0 \rightarrow l^- + \dots)}{\Gamma(B^0 \rightarrow l^+ + \dots)} = \frac{(\Delta M/\Gamma)^2}{2 + (\Delta M/\Gamma)^2} \quad (2.1)$$

where  $\Delta M = M_S - M_L$  and  $\Gamma = (\Gamma_L + \Gamma_S)/2$ . CLEO’s published upper limit on the mixing corresponds to

$$r < 0.30 \quad (2.2)$$

which translates to the bound

$$|\Delta M/\Gamma| < .93. \quad (2.3)$$

This bound uses the assumption  $\tau_{B^0} = \tau_{B^\pm}$ . Recently reported data could be interpreted as improving the bound, or as loosening the lifetime constraint.

Neglecting the  $H - W$  diagram, and approximating the loop integrals, we find

$$\Delta M = \frac{G_F^2 f_B^2 m_B B_B s_1^2 s_2^2 m_t^2}{6\pi^2} \left[ 1 + \frac{1}{4} \left( \frac{\xi}{\eta} \right)^4 \frac{m_t^2}{M_H^2} \right], \quad (2.4)$$

where  $\xi/\eta$  is the VEV of the Higgs doublet coupling to the up-type quarks divided by that of the doublet coupling to down-type quarks. Here  $M_B$  is the  $B$  meson mass,  $s_1$  is the sine

of the first KM angle, and  $m_t$  is the  $t$  quark mass;  $f_B$  is defined analogously to the pion and kaon decay constants,  $f_\pi$  and  $f_K$ ;  $B_B$  is the bag factor for the  $B$  meson, and  $s_2$  is the sine of the second KM angle. The first four parameters are fairly well-determined; we take  $M_B = 5.3$  GeV,  $s_1 = .23$ ,  $f_B = f_K = .16$  GeV and  $m_t = 45$  GeV ( $m_t$  could be larger, but this would only make our bound better, and it cannot be much smaller; we absorb any uncertainty in  $f_B$  into  $B_B$ ).

In Fig. 1 I show our limit for various values of the bag factor and  $s_2$ .

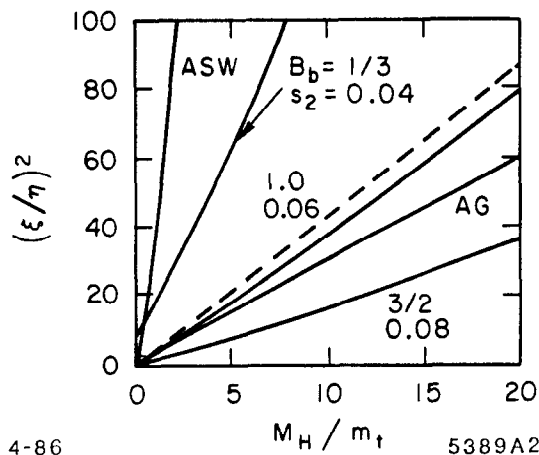


Fig. 1. Limits on  $(\xi/\eta)^2$  versus charged-Higgs-boson mass.

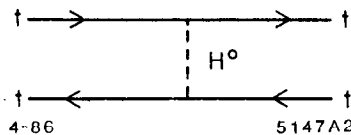
As “reasonable” parameters we pick  $B_B = 1$  and  $s_2 = 0.06$ . The dashed line is the above, approximate calculation, while the solid line is the limit resulting if we evaluate the loop integrals exactly, and include the Higgs- $W$  cross term. I also show our limits for the conservative values  $B_B = 1/3$  and  $s_2 = 0.04$ , and for the “optimistic” values  $B_B = 3/2$  and  $s_2 = 0.08$ —or equivalently, for improved experimental limits on  $B^0 - \bar{B}^0$  mixing. For comparison, I show two previously calculated limits: the first, labeled  $ASW$ ,<sup>[4]</sup> is the limit from  $K\bar{K}$  mixing in the four quark model, and the second, labeled  $AG$ ,<sup>[5]</sup> is the limit determined by considering  $CP$  violation in the neutral  $K$  system. While this second bound is comparable to ours, it requires the additional assumption that the primary contribution to the  $CP$  violation parameter  $\epsilon$  be from the  $W - W$  diagram, rather than from those involving the Higgs, which may not be true.

With the unitarity constraint that the Higgs mass be less than of order 1 TeV, we have an Higgs-mass-independent bound of

$$\frac{\xi}{\eta} \lesssim 10 - 15. \quad (2.5)$$

### 3. Effects of allowed two-Higgs models on toponium physics

The neutral-Higgs ( $H_0$ ) exchange contributes to the toponium potential, with the  $H_0$  coupling enhanced by the ratio  $\xi/\eta$  (I ignore possible mixing effects between the different neutral Higgs).



The new term is an attractive Yukawa, in momentum space

$$-\left(\frac{\xi g m_t}{\eta 2 M_W}\right)^2 \frac{1}{m_H^2 + q^2} \quad \text{or} \quad -\left(\frac{\xi g m_t}{\eta 2 M_W}\right)^2 \frac{e^{-r m_H}}{4\pi r} \quad (3.1)$$

in coordinate space. This has the effect of increasing the wavefunction at the origin, since it pulls in the wavefunctions, and of lowering energy levels (increasing binding energies). It also increases the level spacings, since it affects the lowest lying states the most. The number of states below threshold could change, but not significantly, since states above the 3S are almost unaffected (this will be an unobservable effect, since with the expected resolution of SLC or LEP, we only hope to see the first 2 to 5 states out of the 11 to 13 states below threshold). Other quarkonia are, in principle, affected, though negligibly, due to their light mass.

Let us now consider the  $2S/1P$  splitting. A theorem due to Martin<sup>[7]</sup> states that if  $\Delta V(r) > 0$  (true for all proposed quarkonia potentials), the  $nS$  state lies above the  $(n-1)P$  state, while if  $\Delta V(r) < 0$  for all  $r$  such that  $dV/dr > 0$  (true for the Higgs potential), the  $nS$  state lies below the corresponding  $P$  state. Here we have a qualitative signature of the presence of the Higgs. However, the theorem requires a given condition on  $\Delta V(r)$  to hold for all  $r$ . (The condition  $dV/dr > 0$  holds for all  $r$ , for both potentials.) What happens when the Higgs dominates only near the origin? We might guess that relevant energy levels will be inverted if the Higgs term dominates below some relevant radius, perhaps that of the  $2S$  or  $1P$ . As  $M_H$  increases, the range of the Higgs potential decreases and we need a larger value of  $\xi/\eta$  to keep  $\Delta V < 0$ . This does give a qualitative picture of what happens. We find, numerically, the value of  $\xi/\eta$  at which  $E_{2S} = E_{1P}$ , shown in Fig. 2 for two different potential models.<sup>[8]</sup> The dashed line indicates the charged-Higgs-mass independent bound of the previous section. Level inversion occurs for points in parameter space above the curves shown.

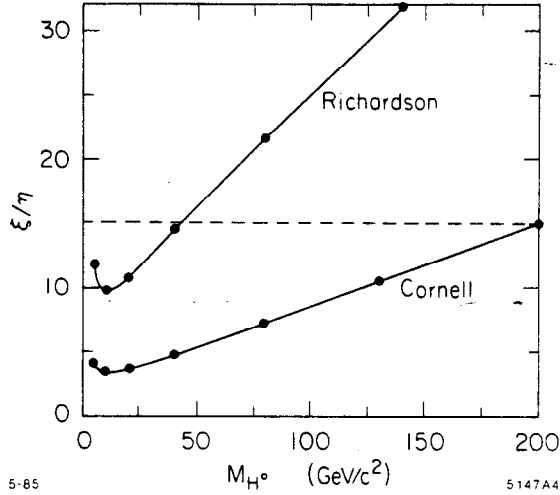


Fig. 2. Minimum value of  $\xi/\eta$  for which level inversion occurs.

We can make a semi-quantitative analysis of the wavefunction change by examining the singular part of the potentials. This goes from  $-c/r$ , where  $c$  is some potential-model-dependent constant, to

$$-\left(c + \left(\frac{\xi g m_t}{\eta 2 M_W}\right)^2 \frac{1}{4\pi}\right) \frac{1}{r}. \quad (3.2)$$

But  $|\psi(0)|^2 \propto (c m_t)^3$  for a Coulomb potential, so we expect the dependence

$$|\psi(0)|^{2/3} = |\psi(0)|_{\xi/\eta=0}^{2/3} [1 + a(\xi/\eta)^2], \quad (3.3)$$

where the constant  $a$  is deduced from Eq. (3.2). Numerically, we find this behaviour for small  $\xi/\eta$  (5 to 10), although  $a$  is smaller than calculated from Eq. (3.2), because of the screening effect of the factor  $e^{-M_H r}$ .

Table 1 shows the effect of the Higgs term for various potentials,<sup>[6]</sup> Higgs masses, and VEV ratios. The Higgs can have striking effects; note, however, the similarity of the Cornell potential without a Higgs term to the Richardson potential with such a term. We have illustrated this problem by picking potentials that are not as physically well motivated as the Richardson potential. We would get similar, though less striking, effects by considering a QCD-inspired potential where one is free to vary  $\Lambda_{\overline{MS}}$ .

— Figure 3 shows  $R(e^+e^- \rightarrow \mu^+\mu^-)$ , for toponium interfering with the  $Z$ , smeared with a beam width of 40 MeV, and  $m_t = 47.5$  GeV. Note the qualitative similarity between the second and third figures.

**Table 1.** Calculated parameters of toponium.  
 $m_t = 50$  GeV (all units GeV to appropriate powers).

Potential	$M_H$	$\xi/\eta$	$\langle r \rangle_{1S}$	$E_{2s} - E_{1s}$	$E_{2s} - E_{1p}$	$\Psi(0)_{1s}$	$\Psi(0)_{2s}/\Psi(0)_{1s}$
Richardson	—	0	.24	.999	.102	8.5	.52
	5	7	.18	1.58	.061	15.1	.42
	10	11	.133	2.37	-.037	26.4	.306
	20	10	.18	1.41	.016	18.0	.41
	40	8.2	.224	1.071	.08	11.4	.49
Cornell	—	0	.144	2.226	.015	23.3	.372
	10	4	.133	2.51	-.005	26.4	.354
Martin	—	0	.419	.455	.127	2.72	.75

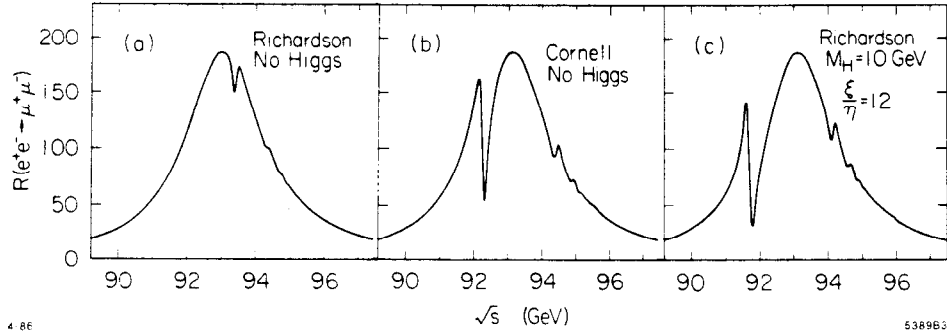


Fig. 3. Effects of varying quarkonium potential.

#### 4. Conclusions

In summary, we have seen that experimental limits on  $B^0 - \bar{B}^0$  mixing yield strong limits on 2-Higgs models. For “reasonable” parameters, we have the bound

$$\left(\frac{\xi}{\eta}\right)^2 < 4.1 \frac{M_H}{m_t}. \quad (4.1)$$

With unitarity, this yields an overall bound of  $\xi/\eta \lesssim 10 - 15$ . The enhanced neutral Higgs couplings allowed by this bound could strongly influence toponium spectroscopy. However, care must be taken in distinguishing this effect from uncertainties in potentials.

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