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No Light Top Quark After All*

YOSEF NIR

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

ABSTRACT

In models with charged Higgs bosons, various bounds on the top mass may not hold. In particular, the bound coming from Z^0 decays and the bound coming from $B-\bar{B}$ mixing can each be avoided. However, these two bounds cannot be *simultaneously* avoided. Consequently, the lower limit $m_t \geq 40\ GeV$ announced by MARK II would be valid even if there existed a light charged Higgs.

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Present limits on the top mass come from various sources:

a. In hadron colliders, the top quark would be produced by either $p\bar{p} \to t\bar{t}$ or $p\bar{p} \to W \to t\bar{b}$. The search for the top is performed through its semi-leptonic decays, with either an e or a μ in the final state. The failure to observe such events gives the following bounds by the CDF, UA2 and UA1 collaborations [1]:

$$m_t \geq \begin{cases} 77\ GeV & \text{CDF} \\ 67\ GeV & \text{UA2} \\ 65\ GeV & \text{UA1} \end{cases} \tag{1}$$

b. The $B-\bar{B}$ mixing measurements by the ARGUS and CLEO collaborations [2] give $x_d = 0.66 \pm 0.11$ (averaging the results of the two experiments). Within the Standard Model, such a substantial mixing can be explained only if the top is heavy enough:

$$m_t \geq 48\ GeV. \tag{2}$$

c. In e^+e^- colliders operating at the Z^0 resonance, the top quark would be produced in $Z^0 \to t\bar{t}$. Isolated leptons from the semi-leptonic t-decays are searched for. The failure to observe such events gives the following bound by the MARK II collaboration [3]:

$$m_t \geq 40.7\ GeV. \tag{3}$$

d. In e^+e^- colliders operating below the Z^0 resonance, the top quark would be produced in $e^+e^- \to \gamma^*, Z^{0*} \to t\bar{t}$. This will increase the value of $R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$. In the TRISTAN experiments, no such effect has been observed up to $\sqrt{s} = 61.4\ GeV$, thus giving the following bound [4]:

$$m_t \gtrsim 30\ GeV. \tag{4}$$

Each of the first three limits [eqs. (1)-(3)] does not necessarily hold in models with two Higgs doublets. Thus it may seem that within such models the limit on the top mass is still $m_t \geq 30\ GeV$. A similar statement was made for bounds similar to those of eqs. (1) and (2) in ref. [5]. Below, we follow the analysis of ref. [5]. However, in this paper we show that, while each of the limits of eq. (2) and eq. (3) may be avoided in two doublet models, it is impossible to evade them *simultaneously*. The conclusion is that, even in the presence of a light charged Higgs, $m_t \geq 40\ GeV$.

Two doublet models imply the existence of five physical scalars: two neutral CP-even scalars, h^0 and H^0, one neutral CP-odd scalar, A^0, and a pair of charged scalars, $H^{\pm}$. It may well be that all scalars but h^0 are much heavier than the electroweak breaking scale [6]. In such a case, they do not modify t-decays and all the above limits (in particular, the $m_t \geq 77\ GeV$ bound from CDF) hold. We assume therefore that the additional scalars are light. In order to avoid unacceptably large Higgs induced flavor changing neutral currents, we need to impose natural flavor conservation [7]. We study the case where one Higgs doublet, Φ_u, couples to charge $+2/3$ quarks, while the other Higgs doublet, Φ_d, couples to charge $-1/3$ quarks and to charged leptons. Our conclusions hold even more strongly in the case that only one of the doublets couples to all fermions.

The limits of eqs. (1) and (3) may be avoided if the charged scalar pair $H^{\pm}$ is light, $m_H \lesssim (m_t - m_b)$. As we are interested-in the possibility that the top mass lies between 30 GeV and 40 GeV, we provisionally fix the charged Higgs mass to be m_H = 25 GeV. Then, in all the relevant range of parameters, the $t \to bH^+$ mode dominates over the W-mediated three body decay. The present experimental lower bound on the mass of the charged Higgs is [8] $m_H \geq 19\ GeV$. The H^+ scalar has the following decay modes:

$$
\begin{aligned}
\Gamma(H^+ \to \ell_i^+ \nu_i) &= \frac{\sqrt{2} G_F}{8\pi} m_H (v_u/v_d)^2 m_{\ell_i}^2, \\
\Gamma(H^+ \to u_{i=1,2} \bar{d}_{j=1,2,3}) &= \frac{\sqrt{2} G_F}{8\pi} 3 m_H |V_{ij}|^2 [(v_d/v_u)^2 m_i^2 + (v_u/v_d)^2 m_j^2],
\end{aligned}
\tag{5}
$$

where v_d and v_u are the VEVs of Φ_d and Φ_u, respectively. For any value of (v_d/v_u), the $(e\nu_e)$ and $(\mu\nu_\mu)$ modes are heavily suppressed. As all hadron collider searches are based on either an e or a μ in the final state, the limits of eq. (1) no longer hold [5].

The bound of eq. (3) is based on the search for isolated leptons. On exactly the same ground as in the hadron collider searches, this signature disappears in the case of a light charged scalar. However, the MARK II collaboration also searched for hadronic events with large momentum sums out of the event plane. This event topology is typical of $t \to bH^+$ when H^+ decays *hadronically.* A new bound is derived [3]:

$$m_t \geq 40\ GeV. \tag{6}$$

According to ref. [3], this bound applies *unless*

$$BR(H^+ \to \tau^+\nu_\tau) \geq 0.7. \tag{7}$$

For a lower top mass, an even larger $(\tau\nu_\tau)$ branching ratio is needed to escape detection by the MARK II analysis. From eq. (5), the condition in eq. (7) can be translated into:

$$(v_d/v_u)^2 \leq 0.39. \tag{8}$$

(We use quark masses as given in ref. [5].) A larger ratio would lead to a larger hadronic branching ratio, bringing us back to the region of validity of the MARK II bound.

Within a two doublet model, $B - \bar{B}$ mixing gets additional contributions from box diagrams with one or two intermediate charged scalars:

$$x_d = \frac{G_F^2 M_W^2 \eta_{QCD}}{6\pi^2} \tau_b M_B (B_B f_B^2) |V_{td}^* V_{tb}|^2 \left[A_{WW} + A_{WH}(v_d/v_u)^2 + A_{HH}(v_d/v_u)^4\right]. \tag{9}$$

The A's are functions of m_t^2/M_W^2 and m_H^2/M_W^2, explicitly given in ref. [9]. Our calculation is similar to ref. [10] ($A_{WW} = y_t f_2(y_t)$ in the language of ref. [10]) with an updated set of parameters:

$$\begin{gathered} x_d \geq 0.55; \quad \tau_b (s_{23})^2 \leq 5.1 \times 10^9\ GeV^{-1}; \\ \sqrt{B_B} f_B \leq 0.2\ GeV; \quad s_{13}/s_{23} \leq 0.14. \end{gathered} \tag{10}$$

This leads to the following constraint:

$$A_{WW} + A_{WH}(v_d/v_u)^2 + A_{HH}(v_d/v_u)^4 \geq 0.32. \tag{11}$$

The constraint $A_{WW} \geq 0.32$ leads to the $m_t \geq 48\ GeV$ bound of eq. (2). With the additional contributions from A_{WH} and A_{HH}, this bound is relaxed [11, 5]. For any chosen value of m_t below 48 GeV, eq. (11) gives a lower bound on $(v_d/v_u)^2$. For $m_t \leq 40$ GeV

$$(v_d/v_u)^2 \geq 0.39. \tag{12}$$

Eqs. (8) and (12) are our main results in this work: A top lighter than 40 GeV could escape detection by the MARK II collaboration if the ratio (v_d/v_u) is small enough to suppress the hadronic decays of a light charged scalar. A top lighter than 40 GeV could still account for the $B-\bar{B}$ mixing measurements by ARGUS and CLEO if the ratio (v_d/v_u) is large enough to enhance contributions from charged scalar exchange box diagrams. The two requirements are incompatible with each other, leaving no room for such a light top quark.

In this analysis we used the 95% C.L. mass limits from MARK II. It is difficult to attribute a confidence level to the bound of eq. (11), as it involves both experimental errors and theoretical uncertainties. However, in order that the bound be saturated, all the quantities in eq. (10) need assume their extreme values. Moreover, for m_t values below 40 GeV, the two bounds of eqs. (8) and (12) rapidly move in opposite directions. We also checked for the effects of varying the charged Higgs mass and found them to be small. When m_H gets larger, its contribution to $B-\bar{B}$ mixing gets smaller, and the bound in eq. (12) becomes even stronger. If m_H is close to the lower experimental limit, the bound on $(v_d/v_u)^2$ from $B-\bar{B}$ mixing is weakened slightly, lowering the bound on m_t by less than 0.5 GeV. Finally, we note that in a two doublet model where only one doublet couples to all fermions, $BR(H^+ \to \text{hadrons}) \sim 0.7$, independently of the VEVs, so that the limit of eq. (6) holds by itself.

Our conclusion is that within two doublet models with a light charged Higgs, various measurements from MARK II, ARGUS and CLEO *combine* to give:

$$m_t \geq 40 \; GeV. \tag{13}$$

This conclusion is expected to soon be tested in a model-independent way, by a precise measurement of the W-width in the CDF experiment. The existence of a charged scalar in the relevant range of masses is expected to soon be tested in the LEP experiment.

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