Implications of the Recent Top Quark Discovery on Two Higgs Doublet Model

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Abstract

Concentrating on the impact of the very recent top quark discovery, we perform a combined analysis of two strongest constraints on the 2 Higgs doublet model, one coming from the recent measurement by CLEO on the inclusive branching ratio of $b \to s\gamma$ decay and the other from the recent LEP data on $Z \to b\bar{b}$ decay. We have included the model predictions for one-loop vertex corrections to $Z \to b\bar{b}$ through $\epsilon_b$. We find that the $\epsilon_b$ constraint excludes most of the less appealing window $\tan \beta \lesssim 1$ at 95% C. L. for the measured top mass from CDF, $m_t = 176 \pm 8 \pm 10$ GeV. Moreover, it excludes $\tan \beta \lesssim 2$ at 95% C. L. for $m_t \gtrsim 176$ GeV. Combining with the $b \to s\gamma$ constraint, only very heavy charged Higgs ($\gtrsim 670$ GeV) is allowed by the measured $m_t$ from CDF.
Very recently, the CDF Collaboration from Fermi Laboratory has finally announced their observation of top quark production in $\bar{p}p$ collisions with the measured top mass $m_t = 176\pm8\pm10$ GeV. The top quark discovery now leaves the Standard Higgs mass $m_H$ the only unknown parameter in the Standard Model (SM). The unknown $m_t$ has long been one of the biggest disadvantages in studying the phenomenology of the SM and its extensions of interest. Now that $m_t$ becomes known at last, one should be able to narrow down the values of $m_t$ in the vicinity of the above central value. Despite the remarkable successes of the SM in its complete agreement with current all experimental data, there is still no experimental information on the nature of its Higgs sector. The 2 Higgs doublet model (2HDM) is one of the mildest extensions of the SM, which has been consistent with experimental data. In this letter, we would like to present the implications of the top quark discovery on the 2HDM in view of the two strongest constraints present in the model, namely, the ones from the flavor-changing radiative decay $b \rightarrow s\gamma$ and $Z \rightarrow b\bar{b}$ decay. In the 2HDM to be considered here, the Higgs sector consists of 2 doublets, $\phi_1$ and $\phi_2$, coupled to the charge -1/3 and +2/3 quarks, respectively, which will ensure the absence of Flavor-Changing Yukawa couplings at the tree level \cite{2}. The physical Higgs spectrum of the model includes two CP-even neutral Higgs($H^0$, $h^0$), one CP-odd neutral Higgs($A^0$), and a pair of charged Higgs($H^\pm$). In addition to the masses of these Higgs, there is another free parameter in the model, which is $\tan \beta \equiv v_2/v_1$, the ratio of the vacuum expectation values of both doublets.

After the first observation by CLEO on the exclusive decay $B \rightarrow K^*\gamma$ \cite{3}, CLEO has recently measured for the first time the inclusive branching ratio of $b \rightarrow s\gamma$ decay to be at 95% C. L. \cite{4},

$$1 \times 10^{-4} < B(b \rightarrow s\gamma) < 4 \times 10^{-4}.$$  

This follows the renewed surge of interests on the $b \rightarrow s\gamma$ decay, spurred by the CLEO bound $B(b \rightarrow s\gamma) < 8.4 \times 10^{-4}$ at 90% C.L. \cite{5}, with which it was pointed out in Ref. \cite{6}.
that the CLEO bound can be violated due to the charged Higgs contribution in the 2HDM and the Minimal Supersymmetric Standard Model (MSSM) basically if $m_{H^\pm}$ is too light, excluding large portion of the charged Higgs parameter space. It has certainly proven that this particular decay mode can provide more stringent constraint on new physics beyond SM than any other experiments\[^7\]. However, it turns out in the 2HDM that the only constraint competing with the one from $b \to s\gamma$ comes from the LEP data on the $Z \to b\bar{b}$ decay\[^8\]. As we know, with the increasing accuracy of the LEP measurements, it has become extremely important performing the precision test of the SM and its extensions\[^9\]. Among several different schemes to analyze precision electroweak tests, we choose a scheme introduced by Altarelli et. al.\[^10, 11\] where four variables, $\epsilon_{1,2,3}$ and $\epsilon_b$ are defined in a model independent way. These four variables correspond to a set of observables $\Gamma_l, \Gamma_b, A_{FB}^l$ and $M_W/M_Z$. Among these variables, $\epsilon_b$ encodes the vertex corrections to $Z \to b\bar{b}$.

In the 2HDM and the MSSM, $b \to s\gamma$ decay receives significant contributions from penguin diagrams with $W^\pm - t$ loop, $H^\pm - t$ loop\[^12\] and the $\chi^\pm_{1,2} - \tilde{t}_{1,2}$ loop\[^13\] only in the MSSM. The expression used for $B(b \to s\gamma)$ in the leading logarithmic (LL) calculations is given by\[^14\]

\[
B(b \to s\gamma) = 6\alpha \frac{\left[\eta^{16/23}A_\gamma + \frac{8}{3}(\eta^{14/23} - \eta^{16/23})A_g + C\right]^2}{\pi I(m_c/m_b)\left[1 - \frac{2}{3\pi}\alpha_s(m_b)f(m_c/m_b)\right]},
\]

(1)

where $\eta = \alpha_s(M_W)/\alpha_s(m_b)$, $I$ is the phase-space factor $I(x) = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$, and $f(m_c/m_b) = 2.41$ the QCD correction factor for the semileptonic decay. $C$ represents the leading-order QCD corrections to the $b \to s\gamma$ amplitude when evaluated at the $\mu = m_b$ scale\[^14\]. We use the 3-loop expressions for $\alpha_s$ and choose $\Lambda_{QCD}$ to obtain $\alpha_s(M_Z)$ consistent with the recent measurements at LEP. In our computations we have used: $\alpha_s(M_Z) = 0.118$,

*A standard model fit to the latest LEP data yields the top mass, $m_t = 178 \pm 11^{+18}_{-19}$ GeV\[^9\], which is in perfect agreement with the measured top mass from CDF.*
$B(b \to ce \bar{v}) = 10.7\%$, $m_b = 4.8$ GeV, and $m_c/m_b = 0.3$. The $A_\gamma, A_g$ are the coefficients of the effective $bs\gamma$ and $bsg$ penguin operators evaluated at the scale $M_W$. Their simplified expressions are given in Ref. [15] in the justifiable limit of negligible gluino and neutralino contributions [13] and degenerate squarks, except for the $\tilde{t}_{1,2}$ which are significantly split by $m_t$. Regarding large uncertainties in the LL QCD corrections, which is mainly due to the choice of renormalization scale $\mu$ and is estimated to be $\approx 25\%$, it has been recently demonstrated by Buras et al. in Ref. [16] that the significant $\mu$ dependence in the LL result can in fact be reduced considerably by including next-to-leading logarithmic (NLL) corrections, which however, involves very complicated calculations of three-loop mixings between certain effective operators and therefore have not been completed yet. In Fig. 1 we present the excluded regions in $(m_{H^\pm}, \tan \beta)$-plane in the 2HDM for $m_t = 163, 176$ GeV, which lie to the left of each dotted curve. The $m_t$ values are of course the central value and the lower limit from the CDF. The contours are obtained using the new 95% C. L. upper bound $B(b \to s\gamma) = 4 \times 10^{-4}$. As expected, the new CLEO bound excludes a large portion of the parameter space. We have also imposed in the figure the lower bound on $\tan \beta$ from $\frac{m_t}{600} \lesssim \tan \beta \lesssim \frac{600}{m_b}$ obtained by demanding that the theory remain perturbative [17]. We see from the figure that at large $\tan \beta$ one can obtain a lower bound on $m_{H^\pm}$ for each value of $m_t$. And we obtain the bounds, $m_{H^\pm} \gtrsim 672, 843$ GeV for $m_t = 163, 176$ GeV, respectively.

Following Ref. [10], $\epsilon_b$ is defined from $\Gamma_b$, the inclusive partial width for $Z \to b\bar{b}$, as

$$\epsilon_b = \frac{g^b_A}{g^b_l} - 1 \quad (2)$$

where $g^b_A (g^b_l)$ is the axial-vector coupling of $Z$ to $b$ ($l$). In the SM, the diagrams for $\epsilon_b$ involve top quarks and $W^\pm$ bosons [18], and the contribution to $\epsilon_b$ depends quadratically on $m_t$ ($\epsilon_b = -G_Fm_t^2/4\sqrt{2}\pi^2 + \cdots$). In supersymmetric models there are additional diagrams
involving Higgs bosons and supersymmetric particles. The charged Higgs contributions have
been calculated in Refs. [19, 8] in the context of the 2HDM, and the contributions involving
supersymmetric particles in Refs. [21, 20]. The main features of the additional supersymmetric
contributions are: (i) a negative contribution from charged Higgs–top exchange
which grows as \( \frac{m_t^2}{\tan^2 \beta} \) for \( \tan \beta \ll \frac{m_t}{m_b} \); (ii) a positive contribution from chargino-stop ex-
change which in this case grows as \( \frac{m_t^2}{\sin^2 \beta} \); and (iii) a contribution from neutralino(neutral
Higgs)–bottom exchange which grows as \( \frac{m_b^2}{\tan^2 \beta} \) and is negligible except for large values
of \( \tan \beta \) (i.e., \( \tan \beta > \frac{m_t}{m_b} \)).

\[ \epsilon_b \] is closely related to the real part of the vertex correction to
\( Z \to b\bar{b}, \) \( \nabla_b \) defined in Ref[21]. The additional diagrams involving \( H^\pm \) bosons have been
calculated in Ref[8, 20, 21, 19]. The charged Higgs contribution to \( \nabla_b \) is given as [21]

\[ \nabla_H^\pm = \frac{\alpha}{4\pi \sin^2 \theta_W} \left[ \frac{2v_L F_L + 2v_R F_R}{v_L^2 + v_R^2} \right], \tag{3} \]

where \( F_{L,R} = F_{L,R}^{(a)} + F_{L,R}^{(b)} + F_{L,R}^{(c)} \) and

\[ F_{L,R}^{(a)} = b_1 (M_{H^+}, m_t, m_b) v_{L,R} \lambda_{L,R}^2, \tag{4} \]

\[ F_{L,R}^{(b)} = \left[ \left( \frac{M_Z^2}{\mu^2} c_0 (M_{H^+}, m_t, m_t) - \frac{1}{2} - c_0 (M_{H^+}, m_t, m_t) \right) v_{R,L}^t \right. \]

\[ + \left. \frac{m_t^2}{\mu^2} c_2 (M_{H^+}, m_t, m_t) v_{L,R}^t \right] \lambda_{L,R}^2, \tag{5} \]

\[ F_{L,R}^{(c)} = c_0 (m_t, M_{H^+}, M_{H^+}) \left( \frac{1}{2} - \sin^2 \theta_W \right) \lambda_{L,R}^2, \tag{6} \]

where \( \mu \) is the renormalization scale and

\[ v_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W, \quad v_R = \frac{1}{3} \sin^2 \theta_W, \tag{7} \]

\[ v_L^t = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W, \quad v_R^t = -\frac{2}{3} \sin^2 \theta_W, \tag{8} \]
\[ \lambda_L = \frac{m_t}{\sqrt{2} M_W \tan \beta}, \quad \lambda_R = \frac{m_b \tan \beta}{\sqrt{2} M_W}. \] (9)

The \( b_1 \) and \( c_{0,2,6} \) above are the reduced Passarino-Veltman functions\[21, 22\]. In our calculation, we neglect the neutral Higgs contributions to \( \nabla_b \) which are all proportional to \( m_b^2 \tan^2 \beta \) and become sizable only for \( \tan \beta > \frac{m_t}{m_b} \) and very light neutral Higgs \( \lesssim 50 \text{ GeV} \), but decreases rapidly to get negligibly small as the Higgs masses become \( \gtrsim 100 \text{ GeV} \[19\]. We also neglect oblique corrections from the Higgs bosons just to avoid introducing more parameters. However, this correction can become sizable when there are large mass splittings between the charged and neutral Higgs, for example, it can grow as \( m_{H^\pm}^2 \) if \( m_{H^\pm} \gg m_{H^0,H^0,A^0} \). Although \( \tan \beta \gg 1 \) seems more appealing because of apparent hierarchy \( m_t \gg m_b \), there are still no convincing arguments against \( \tan \beta < 1 \). Our goal here is to see if one can put a severe constraint from \( \epsilon_b \) in this region. In Fig. 1 we show the contours (solid) of a predicted value of \( \epsilon_b = -0.00733 \), which is the LEP lower limit at 95\%C. L.\[23\]. The excluded regions lie below each solid curve for given \( m_t \). For \( m_t = 176(163) \text{ GeV} \), \( \tan \beta \lesssim 2.0(0.6) \) is ruled out at 95\%C. L. for \( m_{H^\pm} \lesssim 1000 \text{ GeV} \). We note that these strong constraints for \( \tan \beta \lesssim 1 \) stem from large deviations of \( \epsilon_b \) from the SM prediction, which grows as \( m_t^2 / \tan^2 \beta \) as explained above. Combining both \( b \to s\gamma \) and \( \epsilon_b \) constraints, only the region above the solid curve and to the right of the dotted curve survive. For \( m_t = 176(163) \text{ GeV} \), \( \tan \beta \gtrsim 2.0(0.6) \) and \( m_{H^\pm} \gtrsim 843(672) \text{ GeV} \) are allowed at 95\%C. L.

We have also considered other constraints from low-energy data primarily in \( B - \overline{B}, D - \overline{D}, K - \overline{K} \) mixing that exclude low values of \( \tan \beta \[17, 24\]. But it turns out that none of them can hardly compete with the present \( \epsilon_b \) constraint\[23\]. Nevertheless, the CLEO bound is still by far the strongest constraint present in the charged Higgs sector of the model for \( \tan \beta > 1 \). Therefore, we find that \( b \to s\gamma \) and \( \epsilon_b \) serve as the presently strongest and complimentary constraints in 2HDM.
In conclusion, we study the implications of the top quark discovered very recently by CDF by performing a combined analysis of two strongest constraints on the 2 Higgs doublet model, one coming from the recent measurement by CLEO on the inclusive branching ratio of $b \rightarrow s\gamma$ decay and the other from the recent LEP data on $Z \rightarrow b\bar{b}$ decay. We have included the model predictions for one-loop vertex corrections to $Z \rightarrow b\bar{b}$ through $\epsilon_b$. We find that the $\epsilon_b$ constraint excludes most of the less appealing window $\tan\beta \lesssim 1$ at 95% C. L. for the measured top mass, $m_t = 176 \pm 8 \pm 10$ GeV. Moreover, it excludes $\tan\beta \lesssim 2$ at 95% C. L. for $m_t \gtrsim 176$ GeV. Combining with the $b \rightarrow s\gamma$ constraint, only very heavy charged Higgs ($\gtrsim 670$ GeV) is allowed by the measured $m_t$ from CDF.

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Figure Captions

• Figure 1: The regions in \((m_{H^\pm}, \tan \beta)\) plane excluded in 2HDM by the new CLEO bound at 95\%C. L. \(B(b \to s\gamma) < 4.0 \times 10^{-4}\), for \(m_t = 163, 176\ GeV\). The excluded regions lie to the left of each dotted curve. The excluded regions by the latest LEP value at 95\%C. L \(\epsilon_b = -0.00733\) lie below each solid curve. The values of \(m_t\) used are as indicated.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9504369v1