Can $b \to s\gamma$ Close the Supersymmetric Higgs Production Window?

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Abstract

We show that the present limit from CLEO on the inclusive decay $b \to s\gamma$ provides strong constraints on the parameters of the charged Higgs sector in two-Higgs-Doublet-Models. Only a slight improvement in the experimental bound will exclude the region in the Supersymmetric Higgs parameter space which is inaccessible to collider searches.
In the Standard Model (SM) of electroweak interactions, spontaneous symmetry breaking is achieved through a single Higgs doublet, which then generates masses for both the gauge boson and fermion sectors. However, many extensions of the SM predict the existence of two Higgs doublets\cite{1}. The physical spectrum of these models consists of three neutral Higgs scalars, two of which are CP-even \((h^0, H^0)\) while one is CP-odd \((A^0)\), and two charged Higgs scalars \((H^\pm)\). In general, tree-level flavor changing neutral currents are present in two-Higgs-Doublet Models (2HDM), but can naturally be avoided if each fermion type receives mass from the vacuum expectation value (vev) of a single doublet. In one such model, hereafter referred to as Model I, one doublet \((\phi_2)\) provides masses for all fermions and the other doublet \((\phi_1)\) decouples from the fermion sector. This model predicts distinctive phenomenology and has recently been revived in the literature\cite{2}. In a second model (Model II), \(\phi_2\) gives mass to the up-type quarks, while the down-type quarks and charged leptons receive their masses from \(\phi_1\). Supersymmetry and many axion theories predict couplings of the type present in Model II.

Many different types of experiments may reveal the existence of physics beyond the SM. In the case of 2HDM, one could hunt for the enlarged Higgs spectrum directly in both \(e^+e^-\) and hadron colliders. The strongest direct search limits on these particles are provided by LEP\cite{3}; in particular, the mass of the \(H^\pm\) is restricted to be \(\gtrsim M_Z/2\) in all 2HDM. It is also possible that such new physics may manifest itself indirectly in low-energy phenomena. Here, we will show that powerful bounds on the charged Higgs sector in 2HDM arise from the radiative \(b\)-quark decay, \(b \to s\gamma\), and that these constraints surpass those from direct collider searches. As we will see below, the application of these bounds to the particular case of supersymmetric models, could close the window of parameter space where there are no detectable Higgs signatures at colliders. A 90% C.L. upper bound on the branching fraction for this mode, \(B(b \to s\gamma) < 8.4 \times 10^{-4}\), has been obtained by the CLEO Collaboration\cite{4} via an examination of the inclusive photon spectrum in \(B\)-meson
decays. Recent detector refinements coupled with increasing integrated luminosity leads us to anticipate that either the current limit will be strengthened, or the decay may actually be observed in the near future.

Before presenting our results, we first briefly describe the nomenclature of 2HDM. Each doublet obtains a vev $v_i$, subject only to the constraint that $v_1^2 + v_2^2 = v^2$, where $v$ is the usual vev present in the SM. The charged Higgs interactions with fermions are then governed by the Lagrangian

$$\mathcal{L} = \frac{g}{2\sqrt{2} M_W} H^\pm [V_{ij} m_u A_u \bar{u}_i (1 - \gamma_5) d_j$$

$$+ V_{ij} m_d A_d \bar{u}_i (1 + \gamma_5) d_j + m_\ell A_\ell \bar{\nu}_i (1 + \gamma_5) \ell] + \text{h.c.},$$

where $g$ is the usual SU(2)$_L$ coupling constant and $V_{ij}$ is the appropriate element of the Kobayashi Maskawa (KM) matrix. In Model I, $A_u = \cot \beta$ and $A_d = A_\ell = -\cot \beta$, and in Model II, $A_u = \cot \beta$ and $A_d = A_\ell = \tan \beta$, where $\tan \beta \equiv v_2/v_1$ is the ratio of vevs. In a general 2HDM, the mass $m_{H^\pm}$ and $\tan \beta$ are a priori free parameters, as are the masses of all the neutral Higgs fields. However, in supersymmetric models, mass relationships exist between the various Higgs scalars. At tree-level, in such models, only two parameters are required to fix the masses and couplings of the entire scalar sector, but once radiative corrections are included[5], the values of the top-quark and squark masses also need to be specified.

The transition $b \to s\gamma$ proceeds through electromagnetic penguin diagrams, which involve the top-quark, together with a $H^\pm$ or SM $W^\pm$ boson in the loop. The expression for the branching fraction in 2HDM is given in the literature[3]. To fully appreciate our results, it is important to observe the $\tan \beta$ dependence in the transition amplitude for both models. At the $W$ scale the coefficients of the operators which mediate this transition take the generic form

$$c_i(M_W) = A_W (m_t^2/M_W^2) + \lambda A_H^1 (m_t^2/m_{H^\pm}^2) + \frac{1}{\tan \beta^2} A_H^2 (m_t^2/m_{H^\pm}^2),$$

(2)
where $\lambda = -1/\tan\beta^2$, +1 in Models I and II, respectively. $A_W$ corresponds to the SM amplitude and $A_{H}^{1,2}$ represent the $H^\pm$ contributions; their analytic form is given for each contributing operator in Ref. 6. We employ the explicit form of the QCD corrections as stated in Eqns. (4.2) and (4.6) of Grinstein et al.\cite{6}. In order to evaluate these corrections, we use the 3-loop expression for $\alpha_s$ and fit the value of the QCD scale $\Lambda$ to obtain consistency with measurements\cite{3} of $\alpha_s(M_Z^2)$ at LEP. In the SM, this procedure yields $B(b \rightarrow s\gamma) = (2.56 - 3.94) \times 10^{-4}$ for $m_t$ in the range 90 – 200 GeV.

The dependency of the branching fraction on $m_t$, $m_{H^\pm}$, and $\tan\beta$ in both Models I and II is explicitly presented in Ref. 7. Enhancements over the SM rate only occur in Model I for small values of $\tan\beta$. This is due to the fact that the $H^\pm$ contributions to the amplitude are always scaled as $\cot^2\beta$, as seen in Eqn. 2. We also note that a destructive interference between the $H^\pm$ and $W$ contributions is possible for some values of the parameters due to the minus sign in Eqn. 2. In Model II, large enhancements also appear for small values of $\tan\beta$, but more importantly, the branching fraction is found to always be larger than that of the SM. This occurs independently of the value of $\tan\beta$ due to the presence of the term $A_{H}^1$. For certain ranges of the model parameters, the resulting value of $B(b \rightarrow s\gamma)$ exceeds the CLEO bound, and consistency with this limit thus excludes part of the $m_{H^\pm} - \tan\beta$ plane for a fixed value of $m_t$. This is shown in Fig. 1 for both models, where the excluded region lies to the left and beneath the curves. We see that in Model I only a small region of the parameter space is excluded, regardless of the value of $m_t$, however, in Model II a lower limit on $m_{H^\pm}$ is obtained for all values of $\tan\beta$ for the reasons discussed above. For example, with $m_t = 150$ GeV, we find that $m_{H^\pm} > 110$ GeV at large $\tan\beta$, and that even stronger bounds on $m_{H^\pm}$ result for values of $\tan\beta \lesssim 1$. If the CLEO limit were to substantially improve, the constraints in Model II would strengthen drastically, while those in Model I would be essentially unchanged. In performing our calculations, we have tried to be as conservative as possible. We scale $\Gamma(b \rightarrow s\gamma)$ to the $b$-quark semi-leptonic decay
width employing both QCD and phase space corrections (taking $m_c/m_b = 0.3$) to $b \rightarrow ce\bar{\nu}_e$, and take $B(b \rightarrow ce\bar{\nu}_e) = 10.8\%$ (Ref. 8). This procedure removes the sensitive dependence of the $b \rightarrow s\gamma$ rate to the values of the KM matrix elements. The precise value of $m_b$ (we set $m_b = 5$ GeV) that is used in the QCD corrections and phase space factors can have a sizable effect. For example, if $m_b = 4.5$ GeV were taken, the bound on $m_{H^\pm}$ in Model II would increase to 165 GeV for $m_t = 150$ GeV in the large tan $\beta$ limit. QCD corrections which include the effects of separate mass scales for $m_t > M_W$ are found[9] to increase the radiative decay rate by a few percent, but have not been used here, since a separate scale for $m_{H^\pm}$ should also be taken into account. However, we expect that this effect would not be too large since the running of $\alpha_s$ is slow between pairs of heavier mass scales.

To show the power of this indirect search technique, we present in Fig. 2 the branching fraction for Model II in the limit of large tan $\beta$ as a function of $m_t$ with $m_{H^\pm} = m_t - m_b$. If the actual value (or future upper bound) for the branching fraction were to lie below the solid curve, then the decay $t \rightarrow bH^\pm$ is kinematically forbidden for a particular value of $m_t$. For example, the present CLEO result implies that $t \rightarrow bH^\pm$ is already excluded for $m_t \gtrsim 215$ GeV. We see that if the CLEO upper limit were to improve to $6 \times 10^{-4}$, then this decay mode of the top-quark would be excluded for all values of the model parameters. Here, we made use of the large tan $\beta$ limit, since it minimizes the $H^\pm$ contributions to $b \rightarrow s\gamma$.

In the supersymmetric case, the bounds shown in Fig. 1b are more conventionally displayed as an allowed region in the tan $\beta - m_A$ plane, where $m_A$ is the mass of the CP-odd field. This is displayed in Fig. 3a for various values of $m_t$, where the radiative corrections to the SUSY mass relations have been employed assuming $M_{SUSY} = 1$ TeV. We find that our results depend only weakly on the exact value chosen for the squark masses. For $m_t = 150$ GeV, the excluded region is comparable to what can be explored[10] by LEP I and II. The region of supersymmetric parameter space which remains is exactly
that in which the lightest CP-even scalar behaves like the SM Higgs. Figure 3b shows
the growth in the size of the excluded region if the CLEO bound were to improve to
\( B(b \to s\gamma) < 4, 5, 6, \text{ or } 7 \times 10^{-4} \), assuming \( m_t = 150 \) GeV. If \( B < 6 \times 10^{-4} \) then the
window of parameter space left uncovered\[10\] by both \( e^+e^- \) and hadron collider searches
would be excluded. This would imply that the SSC/LHC could cover the entire remaining
allowed supersymmetric Higgs parameter region.

We note that in supersymmetric theories, other super-particles can also contribute
to the one-loop decay \( b \to s\gamma \), and generally lead to a further enhancement in the rate\[11\].
However, a complete examination of the full supersymmetric parameter space needs to
be performed to determine if supersymmetric contributions always enhance the branching
fraction. If that were the case, then the limits presented in this paper could be strengthened
in the supersymmetric version of the 2HDM. However, if some range of parameter values
yielded a destructive interference in the \( b \to s\gamma \) amplitude, the bounds in the supersym-
metric 2HDM could become weaker.

In conclusion, we have shown that the decay \( b \to s\gamma \) is by far the most restrictive
process in constraining the parameters of the charged Higgs sector in 2HDM, yielding
bounds which are stronger than those from other low-energy processes and from direct
collider searches. We anxiously await future results from the CLEO experiment.

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Figure Captions

Figure 1. The excluded regions in the $m_{H^\pm} - \tan \beta$ plane for various values of $m_t$, resulting from the present CLEO bound in (a) Model I and (b) Model II. In each case, from top to bottom, the solid (dashed dot, solid, dotted, and dashed) curve corresponds to $m_t = 210(180, 150, 120, \text{and } 90) \text{ GeV}$. The excluded region lies to the left and below each curve.

Figure 2. $B(b \rightarrow s\gamma)$ as a function of $m_t$, with $m_{H^\pm} = m_t - m_b$ in the large $\tan \beta$ limit in Model II.

Figure 3. (a) The excluded region from the present CLEO limit in the $\tan \beta - m_A$ plane for various values of $m_t$ as indicated. (b) Excluded regions for $m_t = 150 \text{ GeV}$, if the CLEO bound was improved to $B < 4, 5, 6 \text{ or } 7 \times 10^{-4}$. In each case, the excluded region lies to the left and below each curve.