Higgs Masses in the Four Generation MSSM

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In the Minimal Supersymmetric Standard Model (MSSM) with three generations of fermions, there is a stringent upper bound on the mass of the lightest neutral Higgs $h$, and the mass of the charged Higgs $H^+$, must be close (within tens of GeV) to the heavier neutral Higgs, $H$, and the pseudoscalar Higgs $A$. In this Brief Report, we show that in the four generation MSSM, the upper bound on the $h$ mass is much higher, as high as 400 GeV, and $H^+$ is generally much heavier than the $A$, allowing the $H^+ \rightarrow AW^+$ decay, potentially changing search strategies for both the charged Higgs and the pseudoscalar. The $H$ mass, on the other hand, remains within tens of GeV of the charged Higgs mass.

I. INTRODUCTION

One of the most important constraints on supersymmetric models comes from considerations of the mass of the lightest neutral Higgs $h$. In the minimal supersymmetric standard model (MSSM), the mass of the $h$ field at tree level \[ M^2_{H^+} = M^2_A + M^2_W \] (1)

where $A$ is the pseudoscalar Higgs mass. Thus, the charged Higgs mass cannot be much heavier than the pseudoscalar, and the decay $H^+ \rightarrow AW^+$ is kinematically forbidden. Similar considerations involving the mass of the heavier neutral scalar, $H$, show that at tree level

$M^2_H + M^2_Z = M^2_{H^+} + M^2_Z - M^2_W$ \(2\)

which also shows that the charged Higgs cannot decay into $HW^+$. Radiative corrections to these formulae have been calculated and, as in the neutral case, are typically tens of GeV.

In this Brief Report, we note that one of the simplest extensions of the MSSM substantially changes these bounds; the addition of a sequential fourth generation. Interest in a fourth chiral generation (with a sufficiently heavy neutrino to avoid contributing to the Z width) has fluctuated over the years. In the early part of this decade, it was believed by many that electroweak radiative corrections ruled out a chiral fourth generation. However, this belief was based on the assumption that the quark masses were degenerate. It has been shown [10] that relaxing this assumption allows a fourth generation, and for a mass splitting of $O(10\%)$, the S and T corrections fit inside the one-sigma error ellipse [11].

Since corrections to the above mass relations vary as the fourth power of the top quark mass, it is clear that they could be substantially enhanced by a fourth generation. Since the mass splitting between the $b'$ and $t'$ quarks is much smaller than their masses, we will assume that they are degenerate in our analysis. We will consider masses between 250 and 400 GeV. The lower bound is somewhat lower than current Tevatron limits [12], since it might be possible to weaken these limits if supersymmetric decay modes are allowed. The upper bound comes from the requirement that perturbation theory be valid. Generically, the requirement that the Yukawa couplings, $g_Y$ in the MSSM satisfy the condition $g_Y^2/4\pi < 1$ implies \[ 1/x \tan \beta < x, \]

where $x = \sqrt{2\pi(v/M)^2 - 1}$, $\tan \beta$ is the ratio of vacuum expectation values, $M$ is the fermion mass, and $v = 246$ GeV. This window of $\tan \beta$ closes for masses greater than 500 GeV. Since the Yukawa coupling increases with scale, and we want the model to be valid up to at least a TeV, we will set the upper bound to 400 GeV.

In the next section, we look at the lightest neutral scalar, and then consider the mass relations involving the charged Higgs scalar in Section III. Section IV contains our conclusions.

II. THE LIGHTEST NEUTRAL HIGGS MASS

As noted above, $\tan \beta$ must be fairly close to one in order for perturbation theory to be valid. In this case, the tree level value of the lightest neutral Higgs mass is negligible, and the entire mass must come from radiative corrections. In the three generation case, these corrections have been calculated, first in Ref. [3], and then...
with increasing precision by many others\cite{14}. Generally, the contributions from radiative corrections will not be sufficient to increase the mass above 100 GeV (if the tree level mass is negligible).

In the case of four generations, this is not the case. Some early works exploring four generation supersymmetry models\cite{12} did not really address the possibility of fourth generation quarks above 300 GeV. More recently, an exploration of the electroweak phase transition in the four generation MSSM appeared\cite{10}, but it used a value of $\tan\beta$ which put the $b'$ Yukawa coupling far outside the region of perturbative validity. Last year, Murdoch, et al.\cite{17} discussed ways of extending the validity of perturbation theory in the four generation MSSM. The only recent discussion of the lightest Higgs mass in the four generation MSSM was the work of Fok and Kribs\cite{18}, who plotted the lightest Higgs mass as a function of the heavy quark mass. They did restrict the model to the fourth generation quarks above 300 GeV. More recently, for SUSY scales above several hundred GeV. Even in the four generation MSSM not only possible, but is than that of Eq. (3) by 15 (35) percent.

We see that a large mass for the lightest Higgs boson in the four generation MSSM not only possible, but is likely for SUSY scales above several hundred GeV. Even a mass of close to 400 GeV cannot be excluded.

III. THE CHARGED HIGGS MASS

As was noted earlier, Eq. (1) prevents the decay $H^+ \rightarrow AW^+$ at tree level. This makes detection of the charged Higgs quite difficult, since the $H^+ \rightarrow \bar{t}b, \bar{b}t$ decay has very large backgrounds. Radiative corrections to Eq. (1) can be found in Ref. [6], and when these are modified to account for a fourth generation, the decay may no longer be kinematically forbidden. One obtains an expression\cite{6} for $\Delta m = m_{H^+} - m_A$ which depends primarily on $m_{t'}$ and $m_{SU SY}$. The $\tan\beta$ dependence is very small due to the above requirement of the validity of perturbation theory. The dependence on $m_{t'}$ is illustrated in Figure 2 for several values of $m_{SU SY}$ and $\tan\beta$ fixed to 1. We see that the $H^+ \rightarrow AW^+$ decay becomes kinematically allowed for much of parameter space.

The situation is different with respect to the decay $H^+ \rightarrow HW^+$. Radiative corrections to Eq. (2) are given in Ref. [10], and these can easily be generalized to a fourth generation. We find that $m_H$ is never less than $m_{H^+} - m_W$, and in fact usually $m_{H^+} > m_H$ by tens of GeV. Therefore this decay process is still forbidden, even with higher order corrections.

In addition to the possibility of the decay process $H^+ \rightarrow AW^+$, one has the conventional processes $H^+ \rightarrow \bar{t}b,b\bar{t}$ and, for sufficiently heavy charged Higgs bosons, $H^+ \rightarrow \bar{t}b',b't'$. Furthermore, one can also have $H^+ \rightarrow hW^+$. The latter decay will be small in this case. The reason is that in the limit of $M_A >> 100$ GeV, one has $^2\alpha = -\beta$, and thus the coupling of the light Higgs to the charged Higgs and a $W$, which is proportional to $\cos(\alpha - \beta)$, vanishes as $\tan\beta \approx 1$. Of course, one might also have various supersymmetric decay modes. We will only consider decays into $\bar{t}b, \bar{t}b'$ and $AW^+$.

In Figure 3, we plot the branching ratios of $H^+ \rightarrow AW^+, H^+ \rightarrow \bar{t}b, bt$ and $H^+ \rightarrow \bar{t}b', b't'$ versus $m_{t'}$, choosing $M_{SU SY} = 1000$ GeV and $m_A = 500$ GeV. Note that
If the pseudoscalar mass is 1000 GeV, then one can see from Figure 2 that $H^+ \rightarrow AW^+$ is only allowed for very large values of $m_{t'}$, and the branching ratio for this mode is always less than a percent. For $m_A = 500$ GeV, the $H^+ \rightarrow \bar{t}'b'$, $\bar{b}'t'$ decay rapidly becomes kinematically inaccessible, and the branching ratio for $H^+ \rightarrow AW^+$ can be as large as $20\%$. Note that in this case, the pseudoscalar will primarily decay into $tt$, and observation of the associated $W$ may be the only way to detect it.

IV. CONCLUSIONS

In the MSSM, the Higgs sector is very tightly restricted. There is an upper bound of approximately 130 GeV on the lightest Higgs mass and the charged Higgs mass cannot differ by more than tens of GeV from the pseudoscalar and heavier neutral Higgs masses, thus ruling out two-body decays into these states. In this Brief Report, motivated by recent interest in four generation models, we have considered the effects of radiative correction in the four generation MSSM. The upper bound on the lightest Higgs mass is substantially increased, and can be as large as 400 GeV for reasonable parameter values. The mass splitting between the charged Higgs and pseudoscalar is increased to the point where the $H^+ \rightarrow AW^+$ decay is kinematically allowed, whereas the splitting between the charged Higgs and heavy neutral scalar remains small.

Should a fourth generation exist, it will likely be discovered shortly at the LHC. Our main point is that radiative corrections from these quarks can have major implications for the Higgs sector, not only for the MSSM, but other extensions of the Standard Model.

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