LARGE SQUARK-MIXING IMPACT ON $H^+$ DECAY IN THE MSSM

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We study the decays of the charged Higgs boson $H^+$ within the Minimal Supersymmetric Standard Model. We find that the supersymmetric mode $\tilde{t}\bar{b}$ can dominate the $H^+$ decays in a wide range of the model parameters due to the large Yukawa couplings and mixings of $t$ and $b$. Compared to the conventional modes $\tau^+\nu_\tau$ and $tb$, this mode has very distinctive signatures. This could have a decisive impact on $H^+$ searches at future colliders. We find also that the QCD corrections to the $\tilde{t}\bar{b}$ mode are significant, but that they do not invalidate our tree-level conclusion above. (Invited talk at the 28th International Conference on High Energy Physics, Warsaw, Poland, 25-31 July 1996 (to appear in the proceedings (World Scientific)); Report-no: TGU-20, hep-ph/9706440

In the Minimal Supersymmetric Standard Model (MSSM) two Higgs doublets are necessary, leading to five physical Higgs bosons $h^0, H^0, A^0$ and $H^\pm$. In this article we study the $H^\pm$ decays within the MSSM. If all supersymmetric (SUSY) particles are heavy enough, the $H^\pm$ decays dominantly into $tb$; the decays $H^\pm \rightarrow \tau^+\nu$ and/or $H^\pm \rightarrow W^+h^0$ are dominant below the $tb$ threshold. If the decays into charginos and neutralinos $H^\pm \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^0$ are kinematically allowed, they can be important in a sizable region of the MSSM parameters. Here we extend these studies by including also the SUSY modes $H^\pm \rightarrow \tilde{t}_i\tilde{b}_j$ ($i,j=1,2$). Here $\tilde{t}_i (\tilde{b}_j)$ are the scalar top (scalar bottom) mass eigenstates which are mixtures of $\tilde{t}_L$ and $\tilde{t}_R$ ($\tilde{b}_L$ and $\tilde{b}_R$).

The lighter stop $\tilde{t}_1$ can be much lighter than the other squarks and even lighter than the $t$ quark due to large $t$-mixing being proportional to the top Yukawa coupling $h_t$ and the $t$-mixing parameters $A_t$ and $\mu$. Similarly the lighter sbottom $\tilde{b}_1$ can also be lighter than the other squarks. In the case of large $t$- and $b$-mixings one also expects the $H^\pm t\bar{b}$ coupling to be large since it is essentially proportional to the Yukawa couplings $h_{t,b}$ and the squark-mixing parameters $A_{1,2}$ and $\mu$. Here we show explicitly that the mode $\tilde{t}\bar{b}$ can indeed dominate the $H^+$ decay in a wide range of the MSSM parameters as is expected by the observation above.

In the MSSM the properties of the charginos $\tilde{\chi}_i^\pm$ ($i=1,2$) and neutralinos $\tilde{\chi}_j^0$ ($j=1,\ldots,4$) are completely determined by the parameters $m_t, \mu$ and $\tan\beta = v_2/v_1$, assuming $M' = (5/3)\tan^2\theta_W M$. Here $M(M')$ is the SU(2)(U(1)) gaugino mass, $\mu$ is the higgsino mass parameter, and $v_1(v_2)$ is the vacuum expectation value of the Higgs $H^0(H^\pm)$. Here $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^+} < \ldots < m_{\tilde{\chi}_4^+}$. To specify the squark sector the additional (soft SUSY breaking) parameters $M_Q, M_U, M_D$ (for each generation), and $A$ (for each flavor) are necessary. The mass matrix for stops reads:

$$M^2_{\tilde{t}} = \begin{pmatrix} m_{\tilde{t}_L}^2 & a_{tL} m_t \\ a_{tR} m_t & m_{\tilde{t}_R}^2 \end{pmatrix}$$

with

$$m_{\tilde{t}_L}^2 = M^2_Q + m^2_2 \cos 2\beta (I_1^3 - c_t \sin^2 \theta_W)$$
$$+ m_t^2$$
$$m_{\tilde{t}_R}^2 = M^2_U + m^2_2 \cos 2\beta c_t \sin^2 \theta_W + m_t^2$$
$$a_{tL} m_t = -m_t (A_t + \mu \cot \beta).$$

Here notice our sign conventions of $\mu$ and $A$; for $\mu$ we use the sign convention of Ref.1. For the $b$ system analogous formulae hold but with $M^2_U$ replaced by $M^2_D$ in eq.(2), and instead of eq.(4)

$$a_{bL} m_b = -m_b (A_b + \mu \tan \beta).$$

$\tilde{b}_L - \tilde{b}_R$ mixing may also be important for large $A_b, \mu$, and $\tan\beta$. Analogous formulae hold for the sleptons $\tilde{l}$ and $\tilde{\nu}$.

The masses and couplings of the Higgs bosons $H^\pm, H^0, h^0$ and $A^0$, including radiative corrections, are fixed by $m_{A_\pm}, \tan\beta, m_t, M_Q, M_U, M_D, A_t, A_b$ and $\mu$. $H^0 (h^0)$ and $A^0$ are the heavier/lighter CP-even and CP-odd neutral Higgs bosons, respectively. For $m_{H^\pm}$ we take the tree-level relation $m_{H^\pm}^2 = m_{A_\pm}^2 + m_{W^\pm}^2$, because in all
cases considered here the radiative corrections to $m_{H^+}$ turn out to be very small.

In the following, we take for simplicity $M_{Q} = M_{Q} = M_{B}$ (for the third generation), $M_{L} = M_{Q}$ ($M_{L}$ being a common soft-SUSY-breaking mass of all sleptons), and $A_{t} = A_{b} = A_{t} \equiv A$. Thus we have $m_{H^+}, m_{t}, m_{\mu}, \tan \beta, M_{Q}$, and $A$ as free parameters of the MSSM. The theoretical and experimental constraints for the MSSM basic parameters are described in Refs.4,7.

We calculate the widths of all important modes of $H^+$ decay: $H^+ \rightarrow t\bar{b}, \tau^+\nu, c\bar{s}, \tilde{t}_{i}\tilde{b}_{j}$, $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{0}$, $W^{+}h^{0}, \tilde{t}^{*}\tilde{\nu}$. Formulae for these widths are found in Ref.2. As the squarks of the first two generations are supposed to be heavy, these decays will be strongly phase-space suppressed. In order not to vary too many parameters, in the following we fix $m_{t} = 150$ GeV and $m_{\mu} = 300$ GeV, and take the values of $M$ and $\tan \beta$ such that $m_{\chi_{1}^{0}} \simeq 50$ GeV.

In Fig. 1 the contour lines for the branching ratio $B(\tilde{t}\tilde{b}) = \sum_{i,j=1,2} B(H^+ \rightarrow t\bar{b}_{i})$ are plotted in the $A$-$M_{Q}$ plane for $m_{H^+} = 400$ GeV, $\tan \beta = 2$, $M = 120$ GeV. In the plot we have required $m_{i,j} \geq m_{\chi_{1}^{0}}$ ($\geq 50$ GeV). We see that the branching ratio $B(\tilde{t}\tilde{b})$ can be larger than 70% in a sizable region. In this region this decay mode is much more important than the conventional decay modes. For large $\tan \beta$ ($\tan \beta = 12$) we have obtained a similar result to Fig. 1.

In Fig. 2 we show the $m_{H^+}$ dependence of the important branching ratios for $M_{Q} = 85$ GeV, $A = - 250$ GeV, $\tan \beta = 2$, $M = 120$ GeV. In this case we have: $m_{t_{1}} = 116$ GeV, $m_{t_{2}} = 209$ GeV, $m_{b_{1}} = 81$ GeV, $m_{b_{2}} = 102$ GeV, $m_{\chi_{1}^{0}} = 94$ GeV. We see that above the $t_{1}\bar{b}_{1}$ threshold the $\tilde{t}\tilde{b}$ mode dominates over the conventional modes $t\bar{b}$ and $\tau^+\nu$. For $\tan \beta = 12$ we have obtained a similar result to Fig. 2.

The reason for the dominance of the $\tilde{t}\tilde{b}$ mode is as follows: The modes $t\bar{b}$ and $\tilde{t}\tilde{b}$ (whose couplings to $H^+$ are essentially $h_{t}\cos \beta + h_{b}\sin \beta$ and $\sim (A - \mu \tan \beta)h_{t}\cos \beta + (A - \mu \cot \beta)h_{b}\sin \beta$, respectively) can be strongly enhanced relative to the other modes due to the large Yukawa couplings $h_{t,b}$. In addition, the $\tilde{t}\tilde{b}$ mode can be strongly enhanced relative to the other modes in the case the $\tilde{q}$-mixing parameters $A$ and $\mu$ are large. Moreover in this case $t_{1}$ and $b_{1}$ tend to be light.

Quite generally, $B(\tilde{t}\tilde{b})$ depends on the parameters $M_{Q}, A, m_{t}, \mu, \tan \beta$ and more weakly on $M$. For a given $m_{H^+}$ the strongest dependence is that on $M_{Q}$ to which $m_{t}$ and $m_{b}$ are sensitive (see Fig. 1). $B(\tilde{t}\tilde{b})$ can be quite large in a substantial part of the parameter region kinematically allowed for the $\tilde{t}\tilde{b}$ mode. We find that the dominance of the $\tilde{t}\tilde{b}$ mode is fairly insensitive to the assumption $M_{Q} = M_{L}$. As seen in Fig. 1 the dependence on $A$ is also strong. Concerning the assumption $A_{l} = A_{b} = A_{t}$, we have found no significant change of $B(\tilde{t}\tilde{b})$ as compared to Fig. 2, when we take $A_{b,\tau}/A_{t} = \pm 0.5, \pm 1, \pm 2$ keeping $A_{t} = A$. The dependence of the $H^+\tilde{t}\tilde{b}$ couplings (and $B(\tilde{t}\tilde{b})$) on the parameters $\mu, \tan \beta$ and $m_{t}$ is essentially given by the terms $(A - \mu \tan \beta)h_{t}\cos \beta$ and $(A - \mu \cot \beta)h_{b}\sin \beta$ as mentioned above, where $h_{t} \propto m_{t}$. Hence the dominance of the $\tilde{t}\tilde{b}$ mode becomes more pronounced as $m_{t}$ and/or $\mu$ increase. We also find that $B(\tilde{t}\tilde{b})$ is nearly invariant under $(\mu, A) \rightarrow (-\mu, -A)$.

As for the signatures of the $H^+$ decay, typical $\tilde{t}\tilde{b}$ signals are shown in Table 1. They have to be com-
pared with the conventional t\bar{b} signals.  

\begin{equation}
H^+ \rightarrow t\bar{b} \rightarrow (W^+b)\bar{b} \rightarrow f\bar{f}'bb, \text{ i.e. } 4 \text{ jets}(j's) \text{ or } 2 \text{ j's } + 1 \text{ isolated charged lepton (l') } + \text{ missing energy-momentum (p')}. \end{equation}

Note that B(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^\pm) \simeq 1 \text{ if } m_{\tilde{t}_1} < m_{\tilde{\chi}_1^+}, i.e., \text{ and } m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} < m_\ell, \text{ and for } m_{\tilde{\chi}_1^+} \text{ in cases (a)-(d)) and } B(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) \simeq 0 \text{ otherwise (in cases (e)-(h)).}

As seen in Table 1, the \tilde{t}\tilde{b} signals have general features which distinguish them from the t\bar{b} signals: (i) more p' due to the emission of two LSP's (i.e. \tilde{\chi}_1^0's) and hence less energy-momentum of jets and the isolated l' in case of a short decay chain, or (ii) more jets and/or more isolated l' s in case of a longer decay chain. Moreover, depending on the values of the MSSM parameters, the \tilde{t}\tilde{b} signals could have remarkable features as seen in Table 1: (i) the semileptonic branching ratio of H^+ decay with an isolated l' can vary between \sim 0 \text{ (e.g. in case B}(H^+ \rightarrow \tilde{t}_1\tilde{b}_1 \rightarrow c\tilde{\chi}_1^0b\tilde{\chi}_1^0) \sim 1) \text{ and } \sim 1 \text{ (e.g. in case B}(H^+ \rightarrow \tilde{t}_1\tilde{b}_1 \rightarrow (bl'\bar{\nu})(b\tilde{\chi}_1^0) \rightarrow bl'+b\tilde{\chi}_1^0\bar{\nu} \sim 1); \text{ (ii) production of a single } \sim \text{wrong } \text{sign } l' \text{ in H}^+ \text{ decay (e.g. in case (d,h)) or same-sign dileptons } l'^+l'^+ \text{ (e.g. in case (h)), which could yield same-sign isolated dilepton events } e'^+e'^- \text{ (or } \gamma\gamma) \rightarrow H^+H^- \rightarrow (l^-l'^+0r+l'0l'0) \text{ or } j's + y'; \text{ and so on.}

The identification of the sign of charged leptons and the tagging of b- and c-quark jets, h^0, Z^0 and W^\pm \text{ would be very useful in discriminating the } \tilde{t}\tilde{b} \text{ signals from the t\bar{b} signals as well as in suppressing the background. We see that the } \tilde{t}\tilde{b} \text{ signals are very different from the conventional t\bar{b} and } \tau^+\tau^- \text{ signals. If the } \tilde{t}\tilde{b} \text{ mode really dominates the } H^+ \text{ decay, it decisively influences the signatures of } H^+.

We have shown that the SUSY mode \tilde{t}\tilde{b} can be the most important H^+ decay channel in a large allowed region of the MSSM parameter space due to large t and b quark Yukawa couplings and large t- and b-mixings. The \tilde{t}\tilde{b} mode has very distinctive signatures as compared to the conventional modes \tau^+\tau^- and t\bar{b}. This could decisively influence the H^± search at future colliders. We have found that the QCD corrections to the \tilde{t}\tilde{b} mode are significant, but that they do not invalidate our tree-level conclusion above. Finally, we have obtained a conclusion for the H^0 and A^0 decays (H^0, A^0 \rightarrow \tilde{t}\tilde{b}, ... ) quite similar to one for the H^+ decay.

Acknowledgments

This article is based on Refs.4,5.

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Table 1: The typical $t\bar{b}$ signals of the $H^\pm$ decay in comparison to the conventional $t\bar{b}$ signals. $\not{E}_T$, $j$, $l^\pm$, $Z^{(*)}$, and $f$ denote missing energy-momentum, jet, isolated charged lepton, real (or virtual) $Z^\prime$ boson, and $(q, l^\pm, \nu)$, respectively.
### Table 1

| Typical decay chains | Signatures |
|----------------------|------------|
| **(a) $H^+ \rightarrow \begin{cases} i_1 \rightarrow c \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \end{cases}$** | $2j's + \hat{\phi}$ (more $\hat{\phi}$, less $b$ activity) |
| **(b) $H^+ \rightarrow \begin{cases} i_1 \rightarrow c \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_2 \rightarrow \begin{cases} b(Z\rightarrow \chi^0_1) \rightarrow b(f\bar{f}) \chi^0_1 \\ \text{or} \\ b(h\rightarrow \chi^0_1) \rightarrow b(b\text{ or } \tau^+\tau^-) \chi^0_1 \end{cases} \end{cases}$** | $4j's + \hat{\phi} + 2j's + \hat{\phi}$; $2j's + l^+l^- + \hat{\phi}$ ($Z^0$ or $h^0$ emission; more $b$ activity if $h^0$ or $Z^{\pm}$ to $b\bar{b}$; less $b$ activity if $h^0$ or $Z^{\pm}$ to $l^+l^- + \nu\bar{\nu}$) |
| **(c) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \rightarrow (c \chi^0_1)(bb\text{ or } \tau^+\tau^-) \end{cases}$** | $4j's + \hat{\phi}$; $2j's + \hat{\phi}$; $2j's + l^+l^- + \hat{\phi}$ ($Z^0$ or $h^0$ emission; more $b$ activity if $h^0$ or $Z^0 \rightarrow b\bar{b}$; less $b$ activity if $h^0$ or $Z^0 \rightarrow l^+l^- + \nu\bar{\nu}$) |
| **(d) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \rightarrow (bW^-)(f\bar{f}) \chi^0_1 \rightarrow b(f\bar{f})' f' \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \end{cases}$** | $6j's + \hat{\phi}; 4j's + l^+ + \hat{\phi}$; $2j's + l^+l^- + \hat{\phi}$ ("wrong"-sign single lepton $l$; less $b$ activity) |
| **(e) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \rightarrow (bW^-)(f\bar{f}) \chi^0_1 \rightarrow b(f\bar{f})' f' \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \end{cases}$** | $4j's + \hat{\phi}$; $2j's + l^+ + \hat{\phi}$ (more $\hat{\phi}$) |
| **(f) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \rightarrow b(f\bar{f})' f' \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \end{cases}$** | $4j's + \hat{\phi}$; $2j's + l^+ + \hat{\phi}$ (more $\hat{\phi}$) |
| **(g) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \rightarrow b(f\bar{f})' f' \chi^0_1 \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \rightarrow \begin{cases} b(Z\rightarrow \chi^0_1) \rightarrow b(f\bar{f})' f' \chi^0_1 \\ \text{or} \\ b(h\rightarrow \chi^0_1) \rightarrow b(b\text{ or } \tau^+\tau^-) \chi^0_1 \end{cases} \end{cases}$** | $6j's + \hat{\phi}; 4j's + l^+l^- + \hat{\phi}$; $4j's + l^+ + \hat{\phi}$; $4j's + \hat{\phi}$; $2j's + l^+l^- + \hat{\phi}$; $2j's + l^+ + \hat{\phi}$ ($Z^0$ or $h^0$ emission; more $b$ activity if $h^0$ or $Z^0$ to $b\bar{b}$; trilepton) |
| **(h) $H^+ \rightarrow \begin{cases} i_1 \rightarrow \chi^0_1 \rightarrow (c \chi^0_1)(f\bar{f}) \\ \bar{b}_{1,2} \rightarrow \bar{b} \chi^0_1 \rightarrow (bW^-)(f\bar{f}) \chi^0_1 \rightarrow b(f\bar{f})' f' \chi^0_1 \end{cases}$** | $8j's + \hat{\phi}; 6j's + l^+ + \hat{\phi}$; $4j's + l^+l^- + \hat{\phi}$; $2j's + l^+l^- + \hat{\phi}$ ("wrong"-sign single lepton $l$; same-sign dilepton; trilepton) |