Impact of bosonic decays on the search for $\tilde{t}_1$ and $\tilde{b}_1$ squarks

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Abstract

We show that the bosonic decays of the lighter top and bottom squarks, i.e. $\tilde{t}_1 \rightarrow \tilde{b}_1 + (H^+ \text{ or } W^+)$ and $\tilde{b}_1 \rightarrow \tilde{t}_1 + (H^- \text{ or } W^-)$, can be dominant in a wide range of the MSSM parameters. Compared to the fermionic decays, such as $\tilde{t}_1 \rightarrow b + \tilde{\chi}^0_1$, these bosonic decays can have significantly different decay distributions. We also show that the effect of the supersymmetric QCD running of the quark and squark parameters on the $\tilde{t}_1$ and $\tilde{b}_1$ decay branching ratios is quite dramatic. These could have an important impact on the search for $\tilde{t}_1$ and $\tilde{b}_1$ and the determination of the MSSM parameters at future colliders.

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We study the decays of the lighter top and bottom squarks (i.e. $\tilde{t}_1$ and $\tilde{b}_1$) in the MSSM. They can decay into fermions, i.e. a quark plus a gluino ($\tilde{g}$), neutralino ($\tilde{\chi}^0$) or chargino ($\tilde{\chi}^\pm$). They can also decay into bosons [1]:

\[
\tilde{t}_1 \rightarrow \tilde{b}_1 + (H^+ \text{ or } W^+) , \quad \tilde{b}_1 \rightarrow \tilde{t}_1 + (H^- \text{ or } W^-) .
\]

(1)

In case the mass difference between $\tilde{t}_1$ and $\tilde{b}_1$ is sufficiently large [2], the decays of Eq. (1) are possible. Here we extend the analysis of [1].

The squark mass matrix in the basis $(\tilde{q}_L, \tilde{q}_R)$ with $\tilde{q} = \tilde{t}$ or $\tilde{b}$ is given by [1]

\[
\mathcal{M}_q^2 = \begin{pmatrix} m_{\tilde{q}_L}^2 & a_q m_q \\ a_q m_q & m_{\tilde{q}_R}^2 \end{pmatrix}
\]

(2)

\[
m_{\tilde{q}_L}^2 = M_Q^2 + m_W^2 \cos 2\beta \left(I_3^{\mu} - e_q \sin^2 \theta_W \right) + m_q^2
\]

(3)

\[
m_{\tilde{q}_R}^2 = M_{(\tilde{t}, \tilde{b})}^2 + m_W^2 \cos 2\beta e_q \sin^2 \theta_W + m_q^2
\]

(4)

\[
a_q m_q = \begin{cases} (A_t - \mu \cot \beta) m_t & (\tilde{q} = \tilde{t}) \\ (A_b - \mu \tan \beta) m_b & (\tilde{q} = \tilde{b}) \end{cases}
\]

(5)
We treat the soft SUSY-breaking parameters $M_{\tilde{Q}, \tilde{U}, \tilde{D}}$ and $A_{t,b}$ as free ones since the ratios $M_{\tilde{U}}/M_{\tilde{Q}}, M_{\tilde{D}}/M_{\tilde{Q}}$ and $A_t/A_b$ are highly model-dependent. By diagonalizing the matrix (2) one gets the mass eigenstate $\tilde{q}_1 = \tilde{q}_L \cos \theta_\tilde{q} + \tilde{q}_R \sin \theta_\tilde{q}$. We take $M' = (5/3) \tan^2 \theta_W M$ and $m_\tilde{g} = (\alpha_s(m_\tilde{g})/\alpha_2) M$ with $M, M'$ and $m_\tilde{g}$ being the SU(2), U(1) gaugino and gluino mass, respectively. We denote the mass of the CP-odd Higgs boson $A^0$ as $m_A$. Full expressions of the widths of the squark decays are given in [3].

In case $M_{\tilde{Q}, \tilde{U}, \tilde{D}}$ are relatively large in Eqs.(2-5), for $M_{\tilde{U}} > M_{\tilde{Q}} \gg M_{\tilde{D}}$ with $M_{\tilde{Q}} \gg M_{\tilde{U}}, M_{\tilde{D}}$, and $m_{\tilde{b}_1} > m_{\tilde{t}_1}$, we have $m_{\tilde{b}_1} \approx m_{\tilde{t}_1}$, which may allow the bosonic decays of Eq.(1). We consider two patterns of the squark mass spectrum: $m_{\tilde{t}_1} \gg m_{\tilde{b}_1}$ with ($\tilde{t}_1, \tilde{b}_1) \sim (\tilde{t}_L, \tilde{b}_R)$ for $M_{\tilde{U}} \gg M_{\tilde{Q}} \gg M_{\tilde{D}}$, and $m_{\tilde{t}_1} \gg m_{\tilde{b}_1}$ with ($\tilde{t}_1, \tilde{b}_1) \sim (\tilde{t}_R, \tilde{b}_L)$ for $M_{\tilde{D}} \gg M_{\tilde{Q}} \gg M_{\tilde{U}}$. Thus the bosonic decays considered here are basically the decays of $\tilde{t}_L$ into $\tilde{b}_R$ and $\tilde{b}_L$ into $\tilde{t}_R$.

The leading terms of the squark couplings to $H^\pm$ are given by

$$G(\tilde{t}_1 \tilde{b}_1 H^\pm) \sim h_t(\mu \sin \beta + A_t \cos \beta) \sin \theta_t \cos \theta_b + h_b(\mu \cos \beta + A_b \sin \beta) \sin \theta_t \cos \theta_b.$$ (6)

The Higgs bosons $H^\pm$ couple mainly to $\tilde{q}_L \tilde{q}_R^{*}$ combinations. These couplings are proportional to the Yukawa couplings $h_{t,b}$ and the squark mixing parameters $A_{t,b}$ and $\mu$ (Eq.(6)). Hence the widths of the squark decays into $H^\pm$ may be large for large $A_{t,b}$ and $\mu$. In contrast, the gauge bosons $W^\pm$ couple only to $\tilde{q}_L \tilde{q}_L^{*}$, which results in suppression of the decays into $W^\pm$. However, this suppression is largely compensated by a large extra factor stemming from the contribution of the longitudinally polarized W boson radiation ($\tilde{q}_1 \to \tilde{q}_L^{*} W_L^\pm$). Hence the widths of the squark decays into $W^\pm$ may be large for a sizable $\tilde{q}_L^{*} \tilde{q}_R$ mixing term $a_{\tilde{q}} m_{\tilde{q}}$. On the other hand, the fermionic decays are not enhanced for large $A_{t,b}$ and $\mu$. Therefore the branching ratios of the bosonic decays of Eq.(1) are expected to be large for large $A_{t,b}$ and $\mu$ if the gluino mode is kinematically forbidden.

The widths of the $\tilde{t}_1$ and $\tilde{b}_1$ decays into $H^\pm$ receive very large SUSY-QCD corrections for large $\tan \beta$ in the on-shell (OS) renormalization scheme [3], making the perturbative calculation unreliable. This problem can be solved by carefully defining the relevant tree-level couplings in terms of appropriate running parameters and on-shell squark mixing angles $\theta_\tilde{q}$ [4]. Following Ref.[4], we calculate the tree-level widths of the squark decays by using the corresponding tree-level couplings defined in terms of the SUSY-QCD running parameters $m_{\tilde{q}}(Q)$ and $A_{\tilde{q}}(Q)$ (with $Q =$ (on-shell mass of the decaying squark $m_{\tilde{q},\text{OS}}$)), and the on-shell squark mixing angles $\theta_\tilde{q}$. We call the widths thus obtained as 'renormalization group (RG) improved tree-widths'. Our input parameters are all on-shell ones except $A_b$ which is a running one, i.e. they are $M_{\tilde{t}}, M_{\tilde{b}}, M_{\tilde{Q}(\tilde{t})}, M_{\tilde{U}}, M_{\tilde{D}}, A_b(Q = m_{\tilde{q},\text{OS}}), A_t, \mu, \tan \beta, m_A$, and $M$. $M_{\tilde{Q}(\tilde{q})}$ is the on-shell $M_{\tilde{Q}}$ for the $\tilde{q}$ sector. The procedure for getting all necessary on-shell and SUSY-QCD running parameters is given in [3]. For the calculation of the Standard Model running quark mass $m_{\tilde{q}}(Q)_{\text{SM}}$ from the two-loop RG equations we use the two-loop running $\alpha_s(Q)$ as in [3]. We take $M_t=175\text{GeV}$ and $M_b=5\text{GeV}$. We choose $M_{\tilde{Q}(\tilde{t})} = \frac{2}{3}M_{\tilde{U}} = \frac{1}{3}M_{\tilde{D}} (M_{\tilde{Q}(\tilde{t})}$
\[ \frac{3}{2}M_{\tilde{U}} = \frac{3}{2}M_{\tilde{D}} \] for \( \tilde{t}_1 (\tilde{b}_1) \) decays, and \( A_b(Q = m_{\tilde{q}_{R,OS}}) = A_t \equiv A \) for \( \tilde{q}_1 \) decay, for simplicity. Moreover, we fix \( M = 400 \text{GeV} \) (i.e. \( m_{\tilde{g}} = 1065 \text{GeV} \)) and \( m_A = 150 \text{GeV} \). Thus we have \( M_{\tilde{Q}}(\tilde{t}), A, \mu \) and \( \tan \beta \) as free parameters. In the plots we impose the theoretical and experimental constraints \([3]\).

In Fig.1 we plot in the \( A-\mu \) plane the contours of the \( \tilde{t}_1 \) decay branching ratios of the Higgs boson mode, the gauge boson mode, and the total bosonic modes \( B(\tilde{t}_1 \to \tilde{b}_1 + H^+) \equiv B(\tilde{t}_1 \to \tilde{b}_1 + H^+) + B(\tilde{t}_1 \to \tilde{b}_1 + W^+) \) at the RG-improved tree-level. We show also those of the corresponding branching ratio \( B(\tilde{t}_1 \to \tilde{b}_1 + (H^+, W^+)) \) at the naive (unimproved) tree-level, where all input parameters are bare ones (see Eqs.(2-5)). We see that the \( \tilde{t}_1 \) decays into bosons are dominant in a large region of the \( A-\mu \) plane, especially for large \( |A| \) and/or \( |\mu| \), as we expected. Comparing Fig.1.c with Fig.1.d we find that the effect of running of the quark and squark parameters \( (m_{\tilde{q}}(Q), A_{\tilde{q}}(Q), M_{\tilde{Q}, \tilde{U}, \tilde{D}}(Q)) \)
is quite dramatic. For $\tilde{b}_1$ decays we have obtained similar results to those for the $\tilde{t}_1$ decays.

In Fig.3 of Ref. [3] we show the individual branching ratios of the $\tilde{t}_1$ and $\tilde{b}_1$ decays as a function of $\tan \beta$ for $(A, \mu, M_\tilde{Q}(\tilde{t}))=(-800, -700, 600)$GeV and $(800, 800, 600)$GeV, respectively. We find that the branching ratios of the $\tilde{t}_1$ decays into bosons increase with increasing $\tan \beta$ and become dominant for large $\tan \beta$ ($\gtrsim 20$), while the $\tilde{b}_1$ decays into bosons are dominant in the entire range of $\tan \beta$ shown, as expected.

We find that the dominance of the bosonic modes is fairly insensitive to the choice of the values of $m_A$, $M$, and the ratio $A_b(Q)/A_t$.

In conclusion, we have shown that the $\tilde{t}_1$ and $\tilde{b}_1$ decays into Higgs or gauge bosons can be dominant in a fairly wide MSSM parameter region with large mass difference between $\tilde{t}_1$ and $\tilde{b}_1$, large $|A_{t,b}|$ and/or $|\mu|$, and large $m_{\tilde{g}}$ (and large $\tan \beta$ for the $\tilde{t}_1$ decay). Compared to the conventional fermionic decays these bosonic decays can have significantly different decay distributions. We have also shown that the effect of the SUSY-QCD running of the quark and squark parameters on the $\tilde{t}_1$ and $\tilde{b}_1$ decays is quite dramatic. These could have an important impact on the searches for $\tilde{t}_1$ and $\tilde{b}_1$ and on the determination of the MSSM parameters at future colliders.

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