Impact of SUSY CP Phases on Stop and Sbottom Decays in the MSSM

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Abstract

We study the decays of top squarks and bottom squarks in the Minimal Supersymmetric Standard Model with complex parameters $A_t$, $A_b$ and $\mu$. In a large region of the supersymmetric parameter space the branching ratios of $\tilde{t}_1$ and $\tilde{b}_1$ show a pronounced phase dependence. This could have an important impact on the search for $\tilde{t}_1$ and $\tilde{b}_1$ at a future linear collider and on the determination of the supersymmetric parameters.

1 Introduction

So far most phenomenological studies on production and decay of supersymmetric (SUSY) particles have been performed within the Minimal Supersymmetric Standard Model (MSSM) [1] with real SUSY parameters. In this contribution we analyze the decays of $\tilde{t}_1$ and $\tilde{b}_1$ in the MSSM with complex SUSY parameters. The lighter squark mass eigenstates may be relatively light and could be thoroughly studied at an $e^+e^-$ linear collider.

In the third generation sfermion sector the mixing between the left and right states cannot be neglected because of the effects of the large Yukawa couplings. The left-right mixing terms in the squark mass matrix depend on the higgsino mass parameter $\mu$ and the trilinear scalar couplings $A_q$, $q = t, b$, which may be complex in general. In mSUGRA-type models the phase $\varphi_\mu$ of $\mu$ turns out to be restricted by the experimental data on electron, neutron and mercury electric dipole moments (EDMs) to a range $|\varphi_\mu| \lesssim 0.1 - 0.2$ for an universal scalar mass parameter $M_0 \lesssim 400$ GeV [2, 3, 4]. However, the restriction due to the electron EDM can be circumvented if complex lepton flavour violating terms are present in the slepton sector [5]. The phases of the parameters $A_{t,b}$ are not restricted
at one-loop level by the EDM data but only at two-loop level, resulting in much weaker constraints on these phases [6].

Analyses of the decays of the 3rd generation squarks $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ in the MSSM with real parameters were performed in Refs. [7, 8] and phenomenological studies of production and decay of these particles at future $e^+e^-$ colliders in Ref. [9]. A detailed study how to determine $A_t$ and $A_b$ in the real MSSM with help of the measured polarization of final state top quarks was performed in Ref. [10]. Recently the influence of complex phases on the phenomenology of third generation sleptons has been studied in [11].

In this article we study the effects of the complex phases of $A_q$, $A_b$ and $\mu$ on the partial decay widths and branching ratios of $\tilde{t}_1$ and $\tilde{b}_1$. We assume, that the gaugino mass parameters are real. Especially the effects of the possibly large phases of $A_q$ and $A_b$ can be quite strong, which would have an important impact on the search for $\tilde{t}_1$ and $\tilde{b}_1$ at a future $e^+e^-$ linear collider.

2 $\tilde{q}_L$-$\tilde{q}_R$ mixing

The left-right mixing of the stops and sbottoms is described by a hermitian $2 \times 2$ mass matrix, which in the basis $(\tilde{q}_L, \tilde{q}_R)$ reads

$$\mathcal{L}_M^\tilde{q} = -(\tilde{q}^*_L, \tilde{q}^*_R) \begin{pmatrix} M_{2LL}^2 & M_{2LR}^2 \\ M_{2RL}^2 & M_{2RR}^2 \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix},$$

with

$$M_{2LL}^2 = M_{2LL}^Q + (T^3 - Q_q \sin^2 \theta_W) \cos 2\beta m_Z^2 + m_{\tilde{q}_L}^2,$$

$$M_{2RR}^2 = M_{2RR}^Q + Q_q \sin^2 \theta_W \cos 2\beta m_Z^2 + m_{\tilde{q}_R}^2,$$

$$M_{2RL}^2 = (M_{2LR}^Q)^* = m_q \left( A_q - \mu^*(\tan \beta)^{-2T_q^3} \right),$$

where $m_q$, $Q_q$ and $T^3_q$ are the mass, electric charge and weak isospin of the quark $q = b, t$. $\theta_W$ denotes the weak mixing angle, $\tan \beta = v_2/v_1$ with $v_1$ ($v_2$) being the vacuum expectation value of the Higgs field $H_1^\prime$ ($H_2^0$) and $M_{\tilde{q}} = M_{\tilde{Q}}$ ($M_{\tilde{D}}$) for $q = b$ ($t$). $M_{\tilde{Q}}$, $M_{\tilde{D}}$, $M_{\tilde{U}}$, $A_b$ and $A_t$ are the soft SUSY-breaking parameters of the stop and sbottom system. In case of complex parameters $\mu$ and $A_q$ the off-diagonal elements $M_{2LR}^2 = (M_{2LR}^Q)^*$ are also complex with the phase

$$\varphi_\tilde{q} = \arg \left[ M_{2LR}^2 \right] = \arg \left[ A_q - \mu^*(\tan \beta)^{-2T_q^3} \right].$$

$\varphi_\tilde{q}$ together with the squark mixing angle $\theta_\tilde{q}$ fixes the mass eigenstates of the squarks

$$\begin{align*}
\tilde{q}_1 &= e^{i\varphi_\tilde{q}} \cos \theta_\tilde{q} \tilde{q}_L + \sin \theta_\tilde{q} \tilde{q}_R, \\
\tilde{q}_2 &= -\sin \theta_\tilde{q} \tilde{q}_L + e^{-i\varphi_\tilde{q}} \cos \theta_\tilde{q} \tilde{q}_R
\end{align*}$$

with

$$\cos \theta_\tilde{q} = \frac{-|M_{2LR}^2|}{\sqrt{|M_{2LR}^2|^2 + (m_{\tilde{q}_L}^2 - M_{2LL}^2)^2}}, \quad \sin \theta_\tilde{q} = \frac{M_{2LL}^2 - m_{\tilde{q}_L}^2}{\sqrt{|M_{2LR}^2|^2 + (m_{\tilde{q}_L}^2 - M_{2LL}^2)^2}}.$$
and the mass eigenvalues
\[ m_{q_{1,2}}^2 = \frac{1}{2} \left( (M_{q_{LL}}^2 + M_{q_{RR}}^2) \mp \sqrt{(M_{q_{LL}}^2 - M_{q_{RR}}^2)^2 + 4|M_{q_{LR}}^2|^2} \right). \] (9)

3 Numerical results

In this section we will present numerical results for the phase dependences of the \( \tilde{t}_1 \) and \( \tilde{b}_1 \) partial decay widths and branching ratios. We calculate the partial decay widths in Born approximation. It is known that in some cases the one-loop SUSY QCD corrections are important. The analyses of [8, 12, 13] suggest that a significant part of the one-loop SUSY QCD corrections to certain \( \tilde{t}_1 \) and \( \tilde{b}_1 \) partial decay widths can be incorporated by using an appropriately corrected bottom quark mass. In this spirit we calculate the tree-level widths of the \( \tilde{t}_1 \) and \( \tilde{b}_1 \) decays by using on-shell masses for the kinematic factors, whereas we take running masses for the top and bottom quark for the Yukawa couplings. For definiteness we take \( m_t^\text{run}(m_Z) = 150 \text{ GeV}, m_b^\text{on-shell} = 175 \text{ GeV}, m_b^\text{run}(m_Z) = 3 \text{ GeV} \) and \( m_b^\text{on-shell} = 5 \text{ GeV} \). This approach leads to an “improved” Born approximation, which takes into account an essential part of the one-loop SUSY QCD corrections to the \( \tilde{t}_1 \) and \( \tilde{b}_1 \) partial decay widths and predicts their phase dependences more accurately than the “naive” tree-level calculation.

In the numerical analysis we impose the following conditions in order to fulfill the experimental constraints: \( m_{\tilde{\chi}^\pm_1} > 103 \text{ GeV}, m_{\tilde{\chi}^0_1} > 50 \text{ GeV}, m_{H_1} > 100 \text{ GeV}, m_{\tilde{t}_1,\tilde{b}_1} > 100 \text{ GeV}, m_{\tilde{t}_1,\tilde{b}_1} > m_{\tilde{\chi}^0_1}, \Delta \rho (t - b) < 0.0012 \) [14]. We also calculate the branching ratio for \( b \to s \gamma \) and compare it with the experimentally allowed range \( 2.0 \times 10^{-4} < B(b \to s \gamma) < 4.5 \times 10^{-4} \) [15].

First we discuss the dependence of the \( \tilde{t}_1 \) partial decay widths on \( \varphi_{A_t} \) and \( \varphi_{\mu} \) in two scenarios inspired by the Snowmass Points and Slopes scenarios SPS 1a and SPS 4 [16]. For this we take the squark masses, the squark mixing angles, \( \mu, \tan \beta \) and \( M_2 \) from [16] as input and compute \( |A_t| \) from this with help of eqs. (1) – (4). The relevant parameters for the determination of the partial decay widths are summarized in Table 1. Furthermore, we also look at a scenario with a light \( \tilde{t}_1 \) allowing production of this particle at a 500 GeV linear collider. When varying the phases of \( A_t \) and \( \mu \) we fix three squark masses and the absolute values of the parameters at the given values, calculating \( M_{\tilde{Q}}, M_D \) and \( M_D \) accordingly. Then the fourth squark mass \( m_{\tilde{b}_2} \) (\( m_{\tilde{t}_2} \)) in case of stop (sbottom) decays depends on the phases and varies around the given value.

In Fig. 1 we show the partial decay widths and branching ratios for \( \tilde{t}_1 \to \tilde{\chi}^+_1 b, \tilde{t}_1 \to \tilde{\chi}^0_1 t, \tilde{t}_1 \to \tilde{\chi}^0_2 b \) and \( \tilde{t}_1 \to \tilde{\chi}^0_1 t \) as a function of \( \varphi_{A_t} \) in the scenarios of Table 1 for \( \varphi_{A_b} = \varphi_{\mu} = 0 \). Fig. 1 (a) and (b) are for the SPS 1a inspired scenario. Here the partial decay widths of the chargino channels \( \tilde{t}_1 \to \tilde{\chi}^+_1 b \) show a significant \( \varphi_{A_t} \) dependence, whereas \( \tilde{t}_1 \to \tilde{\chi}^0_2 t \) and \( \tilde{t}_1 \to \tilde{\chi}^0_1 t \) have only a weak phase dependence. For \( \varphi_{A_t} \approx 0, 2\pi \) the decay into \( \tilde{\chi}^0_1 t \) dominates, whereas for \( \varphi_{A_t} \approx \pi \) the decay into \( \tilde{\chi}^+_1 b \) has the largest branching ratio. In Fig. 1 (c) and (d) we show the decays in the SPS 4 inspired scenario. Here all four partial decay widths contribute with comparable size. Again the chargino channels \( \tilde{t}_1 \to \tilde{\chi}^+_1 b \) show the largest \( \varphi_{A_t} \) dependence. However, for \( \varphi_{A_t} \approx 0, 2\pi \) the decay \( \tilde{t}_1 \to \tilde{\chi}^0_2 t \) dominates. In the scenario with a light \( \tilde{t}_1 \) (Fig. 1 (e) and (f)) only the decay channels into \( \tilde{\chi}^0_1 \) and \( \tilde{\chi}^0_2 \) are open. Also
|  | SPS 1a | SPS 4 | light $\tilde{t}_1$ | light $\tilde{b}_1$ |
|---|---|---|---|---|
| $m_{\tilde{t}_1}/\text{GeV}$ | 379.1 | 530.6 | 240.0 | 170.0 |
| $m_{\tilde{t}_2}/\text{GeV}$ | 574.7 | 695.9 | 700.0 | $\approx 729$ |
| $m_{\tilde{b}_1}/\text{GeV}$ | 491.9 | 606.9 | 400.0 | 350.0 |
| $m_{\tilde{b}_2}/\text{GeV}$ | $\approx 540$ | $\approx 709$ | $\approx 662$ | 700.0 |
| $|A_t|/\text{GeV}$ | 465.5 | 498.9 | 600.0 | 600.0 |
| $|\mu|/\text{GeV}$ | 352.4 | 377.0 | 400.0 | 300.0 |
| $\tan\beta$ | 10 | 50 | 6 | 30 |
| $M_2/\text{GeV}$ | 192.7 | 233.2 | 135.0 | 200.0 |
| $m_{H^\pm}/\text{GeV}$ | 401.8 | 416.3 | 900.0 | 150.0 |
| $\tilde{q}$ mixing | $M_{\tilde{Q}} > M_{\tilde{U}}$ | $M_{\tilde{Q}} > M_{\tilde{U}}$ | $M_{\tilde{Q}} > M_{\tilde{U}}$ | $M_{\tilde{Q}} > M_{\tilde{D}}$ |

Table 1: Relevant parameters in scenarios used to discuss the stop and sbottom decays.

In this scenario $\Gamma(\tilde{t}_1 \to \tilde{\chi}^0_1 b)$ shows this clear $\varphi_{A_t}$ dependence, resulting in $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ dominating at $\varphi_{A_t} \approx 0, 2\pi$ and $B(\tilde{t}_1 \to \tilde{\chi}^+ b)$ dominating at $\varphi_{A_t} \approx \pi$. The decay pattern, especially of $\tilde{t}_1 \to \tilde{\chi}^+ b$, can be explained in the following way: In all scenarios we have $|A_t| \gg |\mu|/\tan\beta$, therefore $\theta_t$ depends only weakly on $\varphi_{A_t}$. However, $\varphi_{\tilde{t}} \approx \varphi_{A_t}$ (see eq. (5)), which causes the clear $1 - \cos \varphi_{A_t}$ behavior of $\Gamma(\tilde{t}_1 \to \tilde{\chi}^+ b)$. We have calculated $B(b \to s\gamma)$ in all three scenarios. In the case of SPS 1a we obtain $B(b \to s\gamma)$ in the experimentally allowed range for $0.5\pi < \varphi_{A_t} < 1.5\pi$, whereas for $\varphi_{A_t} \approx 0, 2\pi$ it can reach values up to $5 \times 10^{-4}$. In the case of SPS 4 and the scenario with a light $\tilde{t}_1$ the situation is quite similar, with $B(b \to s\gamma)$ reaching values of $6.5 \times 10^{-4}$ and $5.3 \times 10^{-4}$, respectively, near $\varphi_{A_t} \approx 0, 2\pi$.

In Fig. 2 (a) we show a contour plot for the branching ratio $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ as a function of $\varphi_{A_t}$ and $\varphi_\mu$ for $\varphi_{A_t,\mu} = 0$ in the SPS 1a inspired scenario. The $\varphi_{A_t}$ dependence is stronger than the $\varphi_\mu$ dependence. The reason is that these phase dependences are caused by the $\tilde{t}_L$ - $\tilde{t}_R$ mixing term (eq. (4)), where the $\varphi_\mu$ dependence is suppressed. The $\varphi_\mu$ dependence is somewhat more pronounced for $\varphi_{A_t} \approx 0, 2\pi$ than for $\varphi_{A_t} \approx \pi$. If the constraint $|\varphi_\mu| < 0.1 - 0.2$ from the EDM bounds has to be fulfilled, then only the corresponding bands around $\varphi_\mu = 0, \pi, 2\pi$ are allowed. $B(b \to s\gamma)$ is in agreement with the experimental range in almost the whole $\varphi_{A_t}$ - $\varphi_\mu$ plane: only at $\varphi_{A_t} \approx 0, 2\pi$ and $\varphi_\mu \approx 0, 2\pi$ it can go up to $5 \times 10^{-4}$. In order to discuss the dependence of this branching ratio on $|A_t|$ we show in Fig. 2 (b) the contour plot of $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ as a function of $\varphi_{A_t}$ and $|A_t|$ for $\varphi_{A_b} = \varphi_\mu = 0$ and $|A_t| = |A_b|$. Clearly, the $\varphi_{A_t}$ dependence is strongest for large values of $|A_t|$. The dashed lines mark the contours of $\cos \theta_t$, which are perpendicular to the ones of $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ in a large domain of the parameter space. Thus a simultaneous measurement of $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ and $\cos \theta_t$ might be helpful to disentangle the phase of $A_t$ from its absolute value. As an example a measurement of $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t) = 0.6 \pm 0.1$ and $|\cos \theta_t| = 0.3 \pm 0.02$
Figure 1: (a), (c), (e) Partial decay widths and (b), (d), (f) branching ratios of the decays $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 b$ (solid), $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t$ (dashed), $\tilde{t}_1 \rightarrow \tilde{\chi}_2^+ b$ (dashdotted) and $\tilde{t}_1 \rightarrow \tilde{\chi}_2^0 t$ (dotted) in the SPS 1a and SPS 4 inspired scenarios and the scenario with a light $\tilde{t}_1$ defined in Table 1 for $\varphi_{A_b} = \varphi_{\mu} = 0$. 

would allow to determine $|A_t| \approx 320$ GeV with an error $\Delta(|A_t|) \approx 20$ GeV and $\varphi_{A_t}$ with a
twofold ambiguity $\varphi_{A_t} \approx 0.35\pi$ or $\varphi_{A_t} \approx 1.65\pi$ with an error $\Delta(\varphi_{A_t}) \approx 0.1\pi$. $B(b \to s\gamma)$
is in agreement with the experimental range in almost the whole $\varphi_{A_t}$-$|A_t|$ plane: only at
$\varphi_{A_t} \approx 0, 2\pi$ and $|A_t| \gtrsim 300$ GeV it can go up to $5 \times 10^{-4}$.

![Diagram](image.png)

**Figure 2:** Contours of $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ in the SPS 1a inspired scenario defined in Table 1
for (a) $\varphi_{A_b} = 0$ and (b) $|A_b| = |A_t|$, $\varphi_{A_b} = \varphi_\mu = 0$. The dashed lines in (b) denote the contours of cos $\theta_\tilde{t}$.

In order to discuss the decays of the $\tilde{b}_1$ we choose a scenario with a light $\tilde{b}_1$ and a light
$H^\pm$ as defined in Table 1, where the $\tilde{b}_1$ production at a 800 GeV linear collider is possible
and the decay channel $\tilde{b}_1 \to H^-\tilde{t}_1$ is open. We fix $\tan \beta = 30$, because for small $\tan \beta$ the off-diagonal elements in the sbottom mixing matrix are too small.

We show in Fig. 3 (a) and (b) the partial decay widths and the branching ratios
$\tilde{b}_1 \to \tilde{\chi}_{1,2}^0 b$, $\tilde{b}_1 \to H^-\tilde{t}_1$ and $\tilde{b}_1 \to W^-\tilde{t}_1$ as a function of $\varphi_{A_b}$ taking $|A_b| = |A_t| = 600$ GeV,
$\varphi_\mu = \pi$ and $\varphi_{A_t} = \pi/4$. In the region $0.75\pi < \varphi_{A_b} < 1.75\pi$ the decay $\tilde{b}_1 \to H^-\tilde{t}_1$
dominates. The $\varphi_{A_b}$ dependence of its partial decay width is due to that of the $b_R\tilde{t}_L H^-$
coupling term. The partial decay widths of $\tilde{b}_1 \to \tilde{\chi}_{1,2}^0 b$ are essentially $\varphi_{A_b}$ independent,
because the $\varphi_{A_b}$ dependence of the sbottom mixing matrix elements nearly vanishes. The $\varphi_{A_b}$
dependence of the branching ratios $B(\tilde{b}_1 \to \tilde{\chi}_1^0 b)$ is caused by the $\varphi_{A_b}$ dependence
of the total decay width. In the whole parameter range considered $B(b \to s\gamma)$ satisfies
the experimental limits.

For large $\tan \beta$ one expects also a significant $|A_b|$ dependence of the partial decay width $\Gamma(\tilde{b}_1 \to H^-\tilde{t}_1)$. This can be inferred from Fig. 4 (a), where we show the contour plot of the branching ratio of $\tilde{b}_1 \to H^-\tilde{t}_1$ as a function of $|A_b|$ and $\varphi_{A_b}$, taking $|A_t| = |A_b|$, $\varphi_\mu = \pi$ and $\varphi_{A_t} = \pi/4$. The $\varphi_{A_b}$ dependence is stronger for large values of $|A_b|$. Although
Fig. 4 (a) is similar to Fig. 2 (b), the $|A_b|$ and $\varphi_{A_b}$ dependences in Fig. 4 (a) are mainly
due to the phase dependence of the $b_R\tilde{t}_L H^-$ coupling. The shifting of the symmetry axis
to $\varphi_{A_b} = 1.25\pi$ is caused by the additional phase $\varphi_{A_t} = \pi/4$. Contrary to the mixing in the stop sector $\cos\theta_{\tilde{t}}$ is nearly independent of $|A_b|$ and $\varphi_{A_b}$. Therefore the knowledge of $\cos\theta_{\tilde{t}}$ does not help to disentangle the phase of $A_t$ from its absolute value.

In Fig. 4 (b) we show the contour lines of $B(\tilde{b}_1 \to H^-\tilde{t}_1)$ as a function of $\varphi_{A_b}$ and $\varphi_{A_t}$, for $|A_t| = |A_b| = 600$ GeV, $\varphi_{\mu} = \pi$ and the other parameters (except $\varphi_{A_t}$) as in Fig. 4 (a). As can be seen, the $\varphi_{A_t}$-$\varphi_{A_b}$ correlation is quite strong. The shaded area marks the region which is experimentally excluded because of $B(b \to s\gamma) < 2.0 \times 10^{-4}$. Note, that the constraints from $B(b \to s\gamma)$ are only fulfilled for a small range of values of $\varphi_{A_t}$ in the given scenario with $m_{H^\pm} = 150$ GeV.

4 Conclusion

We have shown that the effect of the CP-violating phases of the supersymmetric parameters $A_t$, $A_b$ and $\mu$ on CP-conserving observables such as the branching ratios of $\tilde{t}_1$ and $\tilde{b}_1$ decays can be strong in a large region of the MSSM parameter space. Especially the branching ratios of the $\tilde{t}_1$ can show a pronounced dependence on $\varphi_{A_t}$ in all decay channels. The dependence of the partial decay widths of the $\tilde{b}_1$ on $\varphi_{A_b}$ are in general quite small with exception of decays into final states containing Higgs bosons. Nevertheless the resulting branching ratios show a clear phase dependence. This could have an important impact on the search for $\tilde{t}_1$ and $\tilde{b}_1$ at a future $e^+e^-$ linear collider and on the determination of the MSSM parameters, especially of $A_t$ and $A_b$ which are not easily accessible otherwise.

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Figure 4: Contours of $B(\tilde{b}_1 \rightarrow H^- \tilde{t}_1)$ in the scenario with a light $\tilde{b}_1$ defined in Table 1 for (a) $|A_b| = |A_t|$, $\varphi_\mu = \pi$, $\varphi_{A_t} = \pi/4$ and (b) $|A_b| = |A_t| = 600$ GeV, $\varphi_\mu = \pi$. The shaded area marks the region, which is excluded by the experimental limit $B(b \rightarrow s\gamma) > 2.0 \times 10^{-4}$.

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