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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 μ. 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 μ and the trilinear scalar couplings A_q, $q = t, b$, which may be complex in general. In mSUGRA-type models the phase φ_μ of μ 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_t, A_b and μ 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_t 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 2×2 mass matrix, which in the basis $(\tilde{q}_L, \tilde{q}_R)$ reads

$$\mathcal{L}_M^{\tilde{q}} = -(\tilde{q}_L^*, \tilde{q}_R^*) \begin{pmatrix} M^2_{\tilde{q}_{LL}} & M^2_{\tilde{q}_{LR}} \\ M^2_{\tilde{q}_{RL}} & M^2_{\tilde{q}_{RR}} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}, \tag{1}$$

with

$$\begin{aligned} M^2_{\tilde{q}_{LL}} &= M^2_{\tilde{Q}} + (T_q^3 - Q_q \sin^2\theta_W) \cos 2\beta \, m_Z^2 + m_q^2, && (2) \\ M^2_{\tilde{q}_{RR}} &= M^2_{\tilde{Q}'} + Q_q \sin^2\theta_W \cos 2\beta \, m_Z^2 + m_q^2, && (3) \\ M^2_{\tilde{q}_{RL}} &= (M^2_{\tilde{q}_{LR}})^* = m_q \left(A_q - \mu^* (\tan\beta)^{-2T_q^3} \right), && (4) \end{aligned}$$

where m_q, Q_q and T_q^3 are the mass, electric charge and weak isospin of the quark $q = b, t$. θ_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_1^0 (H_2^0) and $M_{\tilde{Q}'} = M_{\tilde{D}}$ $(M_{\tilde{U}})$ 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 μ and A_q the off-diagonal elements $M^2_{\tilde{q}_{RL}} = (M^2_{\tilde{q}_{LR}})^*$ are also complex with the phase

$$\varphi_{\tilde{q}} = \arg\left[M^2_{\tilde{q}_{RL}}\right] = \arg\left[A_q - \mu^*(\tan\beta)^{-2T_q^3}\right]. \tag{5}$$

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

$$\begin{aligned} \tilde{q}_1 &= e^{i\varphi_{\tilde{q}}} \cos\theta_{\tilde{q}} \, \tilde{q}_L + \sin\theta_{\tilde{q}} \, \tilde{q}_R \, , && (6) \\ \tilde{q}_2 &= -\sin\theta_{\tilde{q}} \, \tilde{q}_L + e^{-i\varphi_{\tilde{q}}} \cos\theta_{\tilde{q}} \, \tilde{q}_R && (7) \end{aligned}$$

with

$$\cos\theta_{\tilde{q}} = \frac{-|M^2_{\tilde{q}_{LR}}|}{\sqrt{|M^2_{\tilde{q}_{LR}}|^2 + (m^2_{\tilde{q}_1} - M^2_{\tilde{q}_{LL}})^2}}, \quad \sin\theta_{\tilde{q}} = \frac{M^2_{\tilde{q}_{LL}} - m^2_{\tilde{q}_1}}{\sqrt{|M^2_{\tilde{q}_{LR}}|^2 + (m^2_{\tilde{q}_1} - M^2_{\tilde{q}_{LL}})^2}} \tag{8}$$

and the mass eigenvalues

$$m^2_{\tilde{q}_{1,2}} = \frac{1}{2}\left((M^2_{\tilde{q}_{LL}} + M^2_{\tilde{q}_{RR}}) \mp \sqrt{(M^2_{\tilde{q}_{LL}} - M^2_{\tilde{q}_{RR}})^2 + 4|M^2_{\tilde{q}_{LR}}|^2}\right). \tag{9}$$

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 $m_t^{\rm run}(m_Z) = 150$ GeV, $m_t^{\rm on\text{-}shell} = 175$ GeV, $m_b^{\rm run}(m_Z) = 3$ GeV and $m_b^{\rm on\text{-}shell} = 5$ 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: $m_{\tilde{\chi}^\pm_1} > 103$ GeV, $m_{\tilde{\chi}^0_1} > 50$ GeV, $m_{H_1} > 100$ GeV, $m_{\tilde{t}_1,\tilde{b}_1} > 100$ GeV, $m_{\tilde{t}_1,\tilde{b}_1} > m_{\tilde{\chi}^0_1}$, $\Delta\rho(\tilde{t}-\tilde{b}) < 0.0012$ [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 φ_{A_t} and φ_μ 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, μ, $\tan\beta$ 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 μ we fix three squark masses and the absolute values of the parameters at the given values, calculating $M_{\tilde{Q}}$, $M_{\tilde{U}}$ and $M_{\tilde{D}}$ 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 $\tilde{t}_1 \to \tilde{\chi}^+_1 b$, $\tilde{t}_1 \to \tilde{\chi}^0_1 t$, $\tilde{t}_1 \to \tilde{\chi}^+_2 b$ and $\tilde{t}_1 \to \tilde{\chi}^0_2 t$ as a function of φ_{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 $\tilde{t}_1 \to \tilde{\chi}^+_{1,2} b$ show a significant φ_{A_t} dependence, whereas $\tilde{t}_1 \to \tilde{\chi}^0_1 t$ has 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 $\tilde{t}_1 \to \tilde{\chi}^+_{1,2} b$ show the largest φ_{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 $\tilde{\chi}^+_1$ and $\tilde{\chi}^0_1$ are open. Also

	SPS 1a	SPS 4	light $\tilde{t}_1$	light $\tilde{b}_1$
$m_{\tilde{t}_1}$/GeV	379.1	530.6	240.0	170.0
$m_{\tilde{t}_2}$/GeV	574.7	695.9	700.0	≈ 729
$m_{\tilde{b}_1}$/GeV	491.9	606.9	400.0	350.0
$m_{\tilde{b}_2}$/GeV	≈ 540	≈ 709	≈ 662	700.0
$\lvert A_t\rvert$/GeV	465.5	498.9	600.0	600.0
$\lvert\mu\rvert$/GeV	352.4	377.0	400.0	300.0
$\tan\beta$	10	50	6	30
M_2/GeV	192.7	233.2	135.0	200.0
$m_{H^\pm}$/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 $\Gamma(\tilde{t}_1 \to \tilde{\chi}_1^+ b)$ shows this clear φ_{A_t} dependence, resulting in $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ dominating at $\varphi_{A_t} \approx 0, 2\pi$ and $B(\tilde{t}_1 \to \tilde{\chi}_1^+ b)$ dominating at $\varphi_{A_t} \approx \pi$. The decay pattern, especially of $\tilde{t}_1 \to \tilde{\chi}_1^+ b$, can be explained in the following way: In all scenarios we have $|A_t| \gg |\mu|/\tan\beta$, therefore $\theta_{\tilde{t}}$ depends only weakly on φ_{A_t}. However, $\varphi_{\tilde{t}} \approx \varphi_{A_t}$ (see eq. (5)), which causes the clear $1 - \cos\varphi_{A_t}$ behavior of $\Gamma(\tilde{t}_1 \to \tilde{\chi}_1^+ b)$. 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 5×10^{-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 6.5×10^{-4} and 5.3×10^{-4}, respectively, near $\varphi_{A_t} \approx 0, 2\pi$.

In Fig. 2 (a) we show a contour plot for the branching ratio $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ as a function of φ_{A_t} and φ_μ for $\varphi_{A_b} = 0$ in the SPS 1a inspired scenario. The φ_{A_t} dependence is stronger than the φ_μ dependence. The reason is that these phase dependences are caused by the $\tilde{t}_L$ -$\tilde{t}_R$ mixing term (eq. (4)), where the φ_μ dependence is suppressed. The φ_μ 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 φ_{A_t}-φ_μ plane: only at $\varphi_{A_t} \approx 0, 2\pi$ and $\varphi_\mu \approx 0, 2\pi$ it can go up to 5×10^{-4}. In order to discuss the dependence of this branching ratio on $|A_t|$ we show in Fig. 2 (b) the contour plot of $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ as a function of φ_{A_t} and $|A_t|$ for $\varphi_{A_b} = \varphi_\mu = 0$ and $|A_t| = |A_b|$. Clearly, the φ_{A_t} dependence is strongest for large values of $|A_t|$. The dashed lines mark the contours of $\cos\theta_{\tilde{t}}$, which are perpendicular to the ones of $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ in a large domain of the parameter space. Thus a simultaneous measurement of $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t)$ and $\cos\theta_{\tilde{t}}$ might be helpful to disentangle the phase of A_t from its absolute value. As an example a measurement of $B(\tilde{t}_1 \to \tilde{\chi}_1^0 t) = 0.6 \pm 0.1$ and $|\cos\theta_{\tilde{t}}| = 0.3 \pm 0.02$

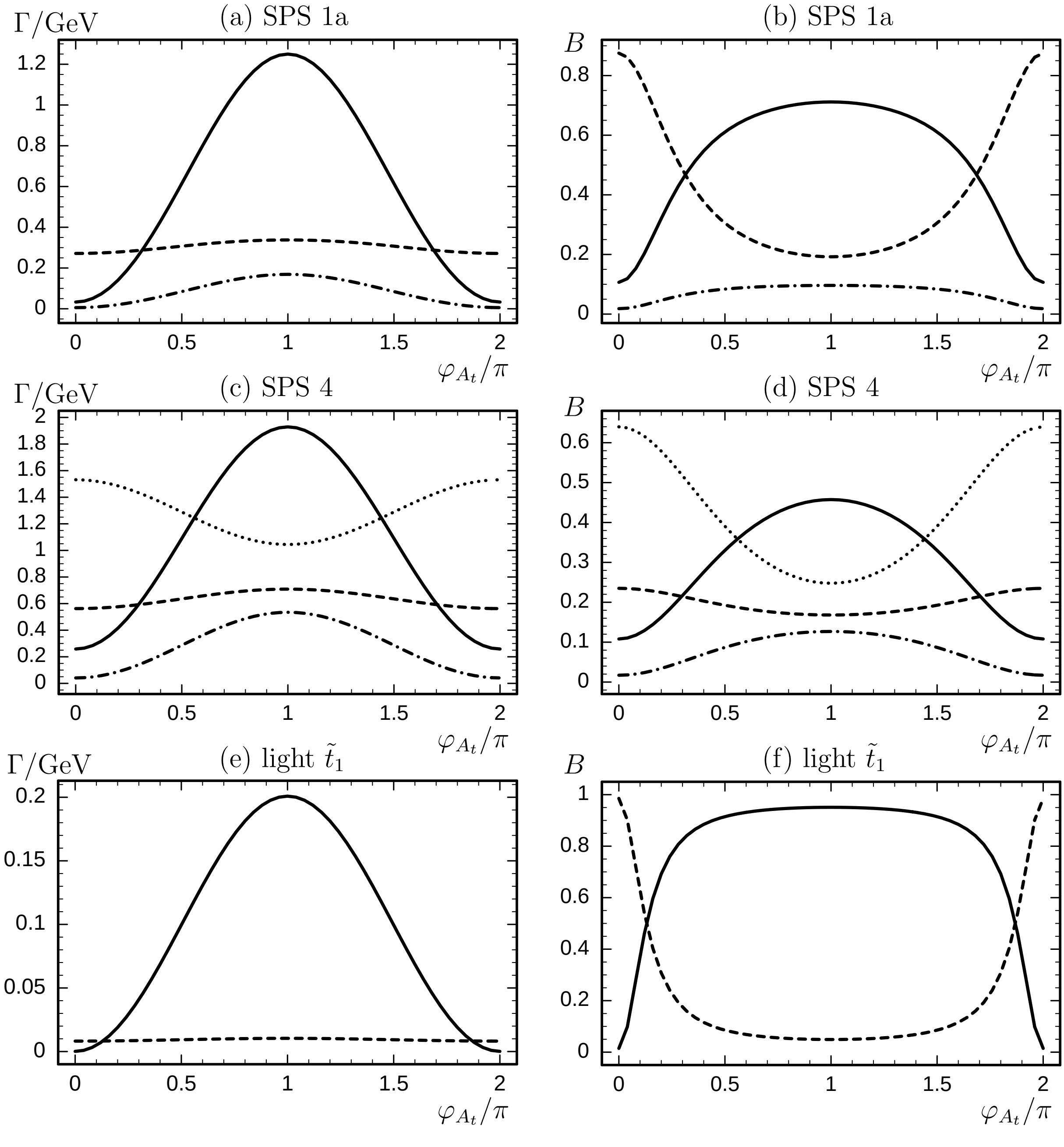

Figure 1: (a), (c), (e) Partial decay widths and (b), (d), (f) branching ratios of the decays $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ (solid), $\tilde{t}_1 \to \tilde{\chi}_1^0 t$ (dashed), $\tilde{t}_1 \to \tilde{\chi}_2^+ b$ (dashdotted) and $\tilde{t}_1 \to \tilde{\chi}_2^0 t$ (dotted) in the SPS 1a 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 φ_{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 φ_{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 5×10^{-4}.

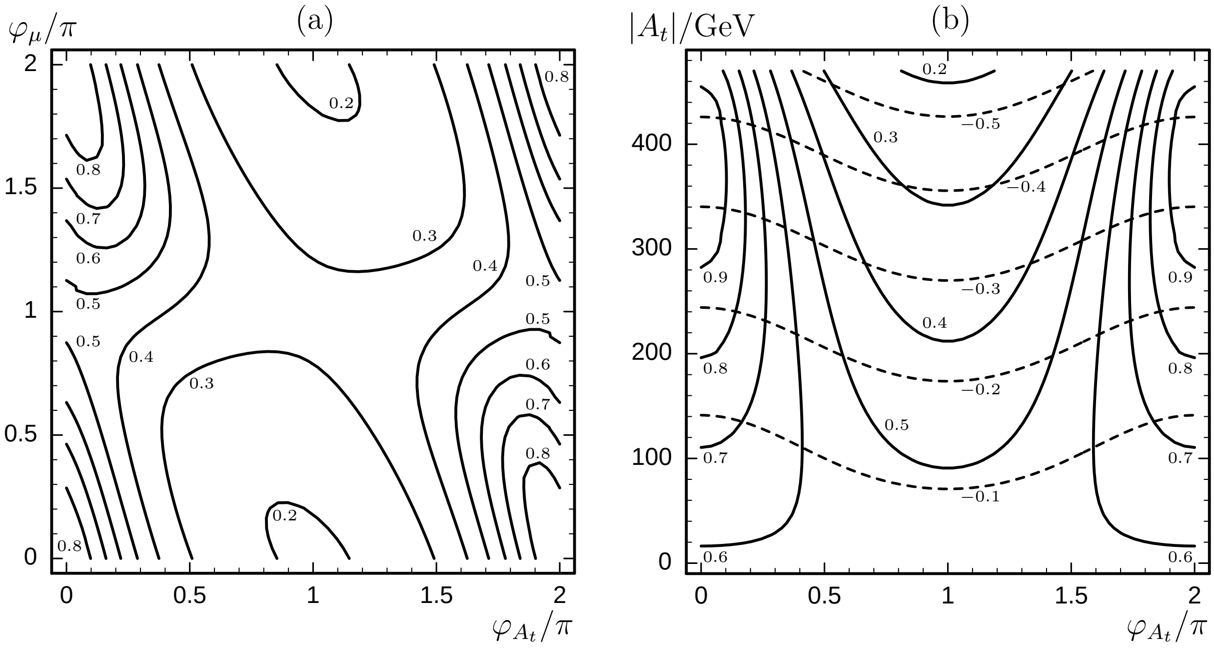

Figure 2: Contours of $B(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$ in the SPS 1a inspired scenario defined in Table 1 for (a) $\varphi_{A_b} = 0$ and (b) $|A_b| = |A_t|$, $\varphi_{A_b} = \varphi_\mu = 0$. The dashed lines in (b) denote the contours of $\cos\theta_{\tilde{t}}$.

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 of $\tilde{b}_1 \to \tilde{\chi}^0_{1,2} b$, $\tilde{b}_1 \to H^-\tilde{t}_1$ and $\tilde{b}_1 \to W^-\tilde{t}_1$ as a function of φ_{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 φ_{A_b} dependence of its partial decay width is due to that of the $\tilde{b}_R\tilde{t}_L H^-$ coupling term. The partial decay widths of $\tilde{b}_1 \to \tilde{\chi}^0_{1,2} b$ are essentially φ_{A_b} independent, because the φ_{A_b} dependence of the sbottom mixing matrix elements nearly vanishes. The φ_{A_b} dependence of the branching ratios $B(\tilde{b}_1 \to \tilde{\chi}^0_{1,2} b)$ is caused by the φ_{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 φ_{A_b}, taking $|A_t| = |A_b|$, $\varphi_\mu = \pi$ and $\varphi_{A_t} = \pi/4$. The φ_{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 φ_{A_b} dependences in Fig. 4 (a) are mainly due to the phase dependence of the $\tilde{b}_R\tilde{t}_L H^-$ coupling. The shifting of the symmetry axis

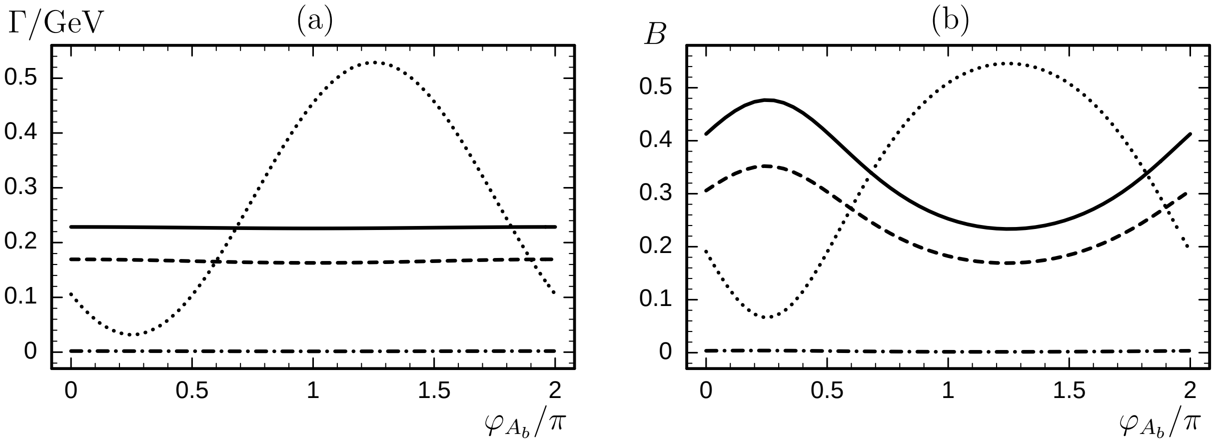

Figure 3: (a) Partial decay widths and (b) branching ratios of the decays $\tilde{b}_1 \to \tilde{\chi}^0_1 b$ (solid), $\tilde{b}_1 \to \tilde{\chi}^0_2 b$ (dashed), $\tilde{b}_1 \to H^- \tilde{t}_1$ (dotted) and $\tilde{b}_1 \to W^- \tilde{t}_1$ (dashdotted) in the scenario with a light $\tilde{b}_1$ defined in Table 1 for $|A_b| = |A_t| = 600$ GeV, $\varphi_\mu = \pi$ and $\varphi_{A_t} = \pi/4$.

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 $\cos\theta_{\tilde{b}}$ is nearly independent of $|A_b|$ and φ_{A_b}. Therefore the knowledge of $\cos\theta_{\tilde{b}}$ does not help to disentangle the phase of A_b 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 φ_{A_b} and φ_{A_t}, for $|A_t| = |A_b| = 600$ GeV, $\varphi_\mu = \pi$ and the other parameters (except φ_{A_t}) as in Fig. 4 (a). As can be seen, the φ_{A_b}-φ_{A_t} 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 φ_{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 μ 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 φ_{A_t} in all decay channels. The dependence of the partial decay widths of the $\tilde{b}_1$ on φ_{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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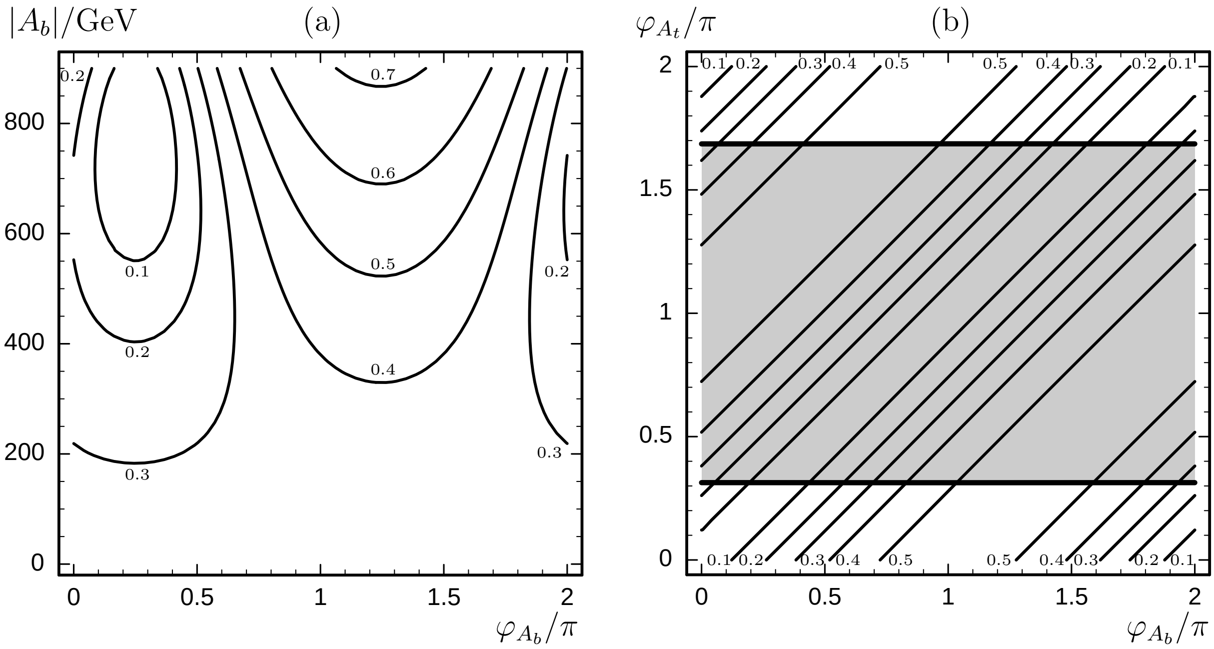

Figure 4: Contours of $B(\tilde{b}_1 \to H^- \tilde{t}_1)$ in the scenario with a light $\tilde{b}_1$ defined in Table 1 for (a) $|A_b| = |A_t|$, $\varphi_\mu = \pi$, $\varphi_{A_t} = \pi/4$ and (b) $|A_b| = |A_t| = 600$ GeV, $\varphi_\mu = \pi$. The shaded area marks the region, which is excluded by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

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