Impact of CP phases on the search for squarks $\tilde{t}$ and $\tilde{b}$

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Contents

§1 Introduction

- *So far most phenomenological studies on SUSY particle searches have been performed in the Minimal Supersymmetric Standard Model (MSSM) with real SUSY parameters.*

- *However it has recently been realized that the effects of the possible complex phases (or CP phases) of the SUSY parameters could be quite significant.*

- *The CP phases can significantly affect not only CP-violating observables (such as lepton EDMs) but also CP-conserving observables (such as decay branching ratios of the sparticles).*

- *Here we study the effect of the possible CP phases on the branching ratios of $\tilde{t}$ and $\tilde{b}$ decays.*

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● ***Purpose of this talk:***

(i)Study $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays in the MSSM with complex SUSY parameters

(ii)Show that the effect of the CP phases of the complex parameters on the branching ratios of $\tilde{t}$ and $\tilde{b}$ decays can be quite strong in a significant portion of the MSSM parameter space.

(iii)Point out that this could have an important impact on the search for $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$, and the determination of the MSSM parameters at future colliders such as LC and LHC.

§2 Basic parameters of MSSM with CP phases

* **Basic parameters of MSSM:**

$\{\tan\beta, M_2, M_1, \mu, A_{t,b}, m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{H^+}\}$ (at $Q = m_Z$)

* We take ($A_{t,b}$, μ, M_1) as complex parameters

| trilinear coupling: $A_{t,b} = |A_{t,b}|\, e^{i\varphi_{A_{t,b}}}$ $(-\pi < \varphi_{A_{t,b}} < \pi)$

| higgsino mass parameter: $\mu = |\mu|\, e^{i\varphi_\mu}$ $(-\pi < \varphi_\mu < \pi)$

| U(1) gaugino mass: $M_1 = |M_1|\, e^{i\varphi_1}$ $(-\pi < \varphi_1 < \pi)$

(note) The basic parameters determine all of the physics here.

(note) We do not assume the GUT relations among the soft-SUSY-breaking parameters such as $M_{\tilde{Q}}$, $M_{\tilde{U}}$ and $M_{\tilde{D}}$, since the relations are highly model-dependent.

(note) In order to improve convergence of perturbative expansion, we use effective running quark masses

$m_b^{run} = 3$ GeV & $m_t^{run} = 150$GeV

for invariant amplitudes.

§3 CP phase dependence of masses, mixings, & couplings

(i) $\tilde{t}$ masses & mixing;

- $\tilde{t}$ mass matrix; $$\mathcal{M}^2_{\tilde{t}} = \begin{array}{c} \begin{array}{cc} \tilde{t}_L & \tilde{t}_R \end{array} \\ \begin{pmatrix} m^2_{\tilde{t}_L} & a_t^* m_t \\ a_t m_t & m^2_{\tilde{t}_R} \end{pmatrix} \end{array}$$ (in $\tilde{t}_L - \tilde{t}_R$ ~~base~~)

$$\begin{cases} m^2_{\tilde{t}_L} = M^2_{\tilde{Q}} + (\mathrm{D\ term})_L + m_t^2 \\ m^2_{\tilde{t}_R} = M^2_{\tilde{U}} + (\mathrm{D\ term})_R + m_t^2 \\ a_t m_t = (A_t - \mu^* \cot\beta) m_t = |a_t m_t| \, e^{i\varphi_{\tilde{t}}} \end{cases}$$

- Diagonalizing the mass matrix we get mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$;

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} e^{i\varphi_{\tilde{t}}} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & e^{-i\varphi_{\tilde{t}}} \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

Masses and mixing angle are given by

$$\begin{cases} m_{\tilde{t}_{1,2}} = \frac{1}{2}\left(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} \mp \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4 m_t^2 |A_t - \mu^* \cot\beta|^2}\right) \\ \tan 2\theta_{\tilde{t}} = \dfrac{2 m_t |A_t - \mu^* \cot\beta|}{m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}} \end{cases}$$

- CP phase dependence;

-- $m_{\tilde{t}_{1,2}}$ and $\theta_{\tilde{t}}$ are sensitive to the phases $(\varphi_{A_t}, \varphi_\mu)$ if $|A_t| \sim |\mu| \cot\beta$.

— $\tilde{t}$-mixing phase $\varphi_{\tilde{t}}$ is sensitive to the phases $\begin{Bmatrix} (\varphi_{A_t}, \varphi_\mu) \\ \varphi_{A_t} \\ \varphi_\mu \end{Bmatrix}$ if $\begin{Bmatrix} |A_t| \sim |\mu| \cot\beta \\ \gg \\ \ll \end{Bmatrix}$.

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(ii) $\tilde{b}$ masses & mixing;

- $\tilde{b}$ **mass matrix;** $$m^2_{\tilde{b}} = \begin{array}{cc} \tilde{b}_L & \tilde{b}_R \end{array} \\ \begin{pmatrix} m^2_{\tilde{b}_L} & a^*_b m_b \\ a_b m_b & m^2_{\tilde{b}_R} \end{pmatrix} \quad (\text{in } \tilde{b}_L - \tilde{b}_R \text{ base})$$

$$\begin{cases} m^2_{\tilde{b}_L} = M^2_{\tilde{Q}} + (D\,\text{term})_L + m^2_b \\ m^2_{\tilde{b}_R} = M^2_{\tilde{D}} + (D\,\text{term})_R + m^2_b \\ a_b m_b = (A_b - \mu^* \tan\beta)\, m_b = |a_b m_b|\, e^{i\varphi_{\tilde{b}}} \end{cases}$$

- ***Diagonalizing the mass matrix we get mass eigenstates***

$\tilde{b}_1$ and $\tilde{b}_2$;

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} e^{i\varphi_{\tilde{b}}} \cos\theta_{\tilde{b}} & \sin\theta_{\tilde{b}} \\ -\sin\theta_{\tilde{b}} & e^{-i\varphi_{\tilde{b}}} \cos\theta_{\tilde{b}} \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \end{pmatrix}$$

Masses and mixing angle are given by

$$\begin{cases} m_{\tilde{b}_{1,2}} = \frac{1}{2}\left(m^2_{\tilde{b}_L} + m^2_{\tilde{b}_R} \mp \sqrt{(m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R})^2 + 4 m^2_b |A_b - \mu^* \tan\beta|^2}\right) \\ \tan 2\theta_{\tilde{b}} = \dfrac{2 m_b |A_b - \mu^* \tan\beta|}{m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R}} \end{cases}$$

- ***CP phase dependence;***

-- ***$m_{\tilde{b}_{1,2}}$ and $\theta_{\tilde{b}}$ are sensitive to the phases $(\varphi_{A_b}, \varphi_\mu)$ if $|A_b| \sim |\mu| \tan\beta$.***

— $\tilde{b}$-mixing phase $\varphi_{\tilde{b}}$ is sensitive

to the phases $\begin{Bmatrix} (\varphi_{A_b}, \varphi_\mu) \\ \varphi_{A_b} \\ \varphi_\mu \end{Bmatrix}$ if $\begin{Bmatrix} |A_b| \sim |\mu| \tan\beta \\ \gg \\ \ll \end{Bmatrix}$.

(iii) $\tilde{\chi}^0$ & $\tilde{\chi}^\pm$ masses & mixings;

- **$\tilde{\chi}^0$ mass matrix;**

$$
\mathcal{M}_{\tilde{\chi}^0} = \begin{array}{c} \begin{array}{cccc} \tilde{B} & \tilde{W}^0 & \tilde{H}_1^0 & \tilde{H}_2^0 \end{array} \\ \begin{pmatrix} M_1 & 0 & -m_Z s\theta_W c\beta & m_Z s\theta_W s\beta \\ 0 & M_2 & m_Z c\theta_W c\beta & -m_Z c\theta_W s\beta \\ -m_Z s\theta_W c\beta & m_Z c\theta_W c\beta & 0 & -\mu \\ m_Z s\theta_W s\beta & -m_Z c\theta_W s\beta & -\mu & 0 \end{pmatrix} \end{array}
$$

- **$\tilde{\chi}^\pm$ mass matrix;**

$$
\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} m_W s\beta \\ \sqrt{2} m_W c\beta & \mu \end{pmatrix}
$$

- **CP phase dependence;**

-- $m_{\tilde{\chi}_i^0}$ and $\tilde{\chi}^0$-mixing matrix are sensitive to (φ_μ, φ_1) for small $\tan\beta$.

-- $m_{\tilde{\chi}_i^\pm}$ and $\tilde{\chi}^\pm$-mixing matrices are sensitive to φ_μ for small $\tan\beta$.

(iv) H_i^0 masses & mixing;

● *H_i^0 mass matrix;*

H_i^0 mass matrix of the Higgs sector with explicit CP violation is given by

(Carena et al., N.P.B586(2000)92)

$$\mathcal{M}^2_{H^0} = \begin{array}{c c} & \overbrace{\phi_1 \quad \phi_2}^{\text{CP even}} \;\; \overbrace{a}^{\text{CP odd}} \\ \begin{array}{c} \phi_1 \\ \phi_2 \\ a \end{array} & \begin{pmatrix} m_1^2 & m_{12}^2 & m_{1a}^2 \\ m_{21}^2 & m_2^2 & m_{2a}^2 \\ m_{a1}^2 & m_{a2}^2 & m_a^2 \end{pmatrix} \end{array}$$

(CP even)-(CP odd) mixing terms m^2_{1a}:
$\phi_{1,2}$ a 2

$m^2_{\underset{2}{1a}} \propto Im(A_{t,b}\mu) \sim |A_{t,b}|\,|\mu|\, \sin(\varphi_{A_{t,b}} + \varphi_\mu)$.

● *CP phase dependence;*

-- *Mass eigenvalues $m_{H_i^0}$ (i=1,2,3) are sensitive to phase sum ($\varphi_{A_{t,b}} + \varphi_\mu$) for small tan$\beta$. ($m_{H_1^0} < m_{H_2^0} < m_{H_3^0}$)*

-- *H_i^0-mixing matrix (O_{ij}) is sensitive to ($\varphi_{A_{t,b}} + \varphi_\mu$) for any tan$\beta$.* $\left(\begin{pmatrix} H_1^0 \\ H_2^0 \\ H_3^0 \end{pmatrix} = \begin{pmatrix} O^T \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ a \end{pmatrix} \right)$

(v) Couplings among interaction-eigenstates;

Squark-chirality flip couplings to Higgs bosons depend on the phases ($\varphi_{A_{t,b}}$, φ_μ):

$C(\tilde{b}_L^\dagger \tilde{t}_R H^-) \sim \sin\beta\ h_t\,(A_t^* \cot\beta + \mu)$

$C(\tilde{t}_L^\dagger \tilde{b}_R H^+) \sim \cos\beta\ h_b\,(A_b^* \tan\beta + \mu)$

$C(\tilde{b}_L^\dagger \tilde{b}_R \phi_1) \sim h_b A_b^*$

$C(\tilde{b}_L^\dagger \tilde{b}_R \phi_2) \sim h_b \mu$

$C(\tilde{b}_L^\dagger \tilde{b}_R a) \sim \cos\beta\ h_b\,(A_b^* \tan\beta + \mu)$

$C(\tilde{t}_L^\dagger \tilde{t}_R a) \sim \sin\beta\ h_t\,(A_t^* \cot\beta + \mu)$

(vi) Decay widths (and hence branching ratios) and cross sections are functions of the masses, mixings and couplings of the involved particles.

(ex) The production cross sections of

$e^+ e^- \to \tilde{t}_i\ \bar{\tilde{t}}_j\ \ \&\ \ \tilde{b}_i\ \bar{\tilde{b}}_j$

are functions of the masses and mixing angles of $\tilde{t}_i$ and $\tilde{b}_i$.

(vii) CP phase dependence of the production cross sections and the decay branching ratios of $\tilde{t}_{1,2}$ & $\tilde{b}_{1,2}$;

From these observations (i)~(vi), we expect that the production cross sections and the decay branching ratios of $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ can be sensitive to the CP phases ($\varphi_{A_{t,b}}$, φ_μ, φ_1) !

§4 Impact of CP phases on $\tilde{t}_{1,2}$ & $\tilde{b}_{1,2}$ decays

(i) $\tilde{t}_{1,2}$ & $\tilde{b}_{1,2}$ decays;

Possible important decays are

$$\tilde{t}_1 \to t\tilde{g},\ t\tilde{\chi}^0_i,\ b\tilde{\chi}^+_j,\ \tilde{b}_1 W^+,\ \tilde{b}_1 H^+$$

$$\tilde{t}_2 \to t\tilde{g},\ t\tilde{\chi}^0_i,\ b\tilde{\chi}^+_j,\ \tilde{t}_1 Z^0,\ \tilde{b}_i W^+,\ \tilde{t}_1 H^0_i,\ \tilde{b}_i H^+$$

$$\tilde{b}_1 \to b\tilde{g},\ b\tilde{\chi}^0_i,\ t\tilde{\chi}^-_j,\ \tilde{t}_1 W^-,\ \tilde{t}_1 H^-$$

$$\tilde{b}_2 \to b\tilde{g},\ b\tilde{\chi}^0_i,\ t\tilde{\chi}^-_j,\ \tilde{b}_1 Z^0,\ \tilde{t}_i W^-,\ \tilde{b}_1 H^0_i,\ \tilde{t}_i H^-$$

(ii) Constraints on MSSM;

In the plots we impose the following conditions in order to respect experimental and theoretical constraints:

-- $m_{\tilde{\chi}^+_1} > 103\,GeV$, $m_{\tilde{\chi}^0_1} > 50\ GeV$, $m_{H^0_1} > 105\,GeV$,

$m_{\tilde{t}_1, \tilde{b}_1} > 100\,GeV$, $m_{\tilde{t}_1, \tilde{b}_1} > m_{\tilde{\chi}^0_1}$ *(LEP limits)*

-- $|A_t|^2 < 3\,(M^2_{\tilde{Q}} + M^2_{\tilde{U}} + m^2_{H_2})$

$|A_b|^2 < 3\,(M^2_{\tilde{Q}} + M^2_{\tilde{D}} + m^2_{H_1})$

(vacuum stability condition)

-- $\Delta\rho(\tilde{t} - \tilde{b}) < 0.0012$

(limit from the precision data on the $\tilde{t}$ - $\tilde{b}$ loop contribution to ρ parameter)

-- $2.0 \times 10^{-4} < B(b \to s\,\gamma) < 4.5 \times 10^{-4}$ *(BELLE, CLEO)*

(assuming the CKM mixing also for the $\tilde{q}$ sector)

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(Note 1) electron & neutron EDM constraints on MSSM;

-- *In general the experimental limits on e & n EDMs strongly constrain the SUSY CP phases.*

-- *One interesting possibility for evading these constraints is to invoke large masses (much above the TeV scale) for the 1st two generations of the sfermions, keeping the 3rd generation sfermions relatively light ($\lesssim$1 TeV).*

-- *In such a scenario the CP phases ($\varphi_1, \varphi_\mu, \varphi_{A_\tau}, \varphi_{A_t}, \varphi_{A_b}$) are practically unconstrained. We take this scenario.*

See Cohen-Kaplan-Nelson, Phys. Lett. B388 (1996) 588;
Carena-Ellis-Pilaftsis-Wagner, Nucl.Phys.B586(2000)92;
Akeroyd-Keum-Recksiegel, Phys. Lett. B 507 (2001) 252.

(iii) Results on $\tilde{t}_1$ decays;

-- (φ_{A_t}, φ_μ) dependence;

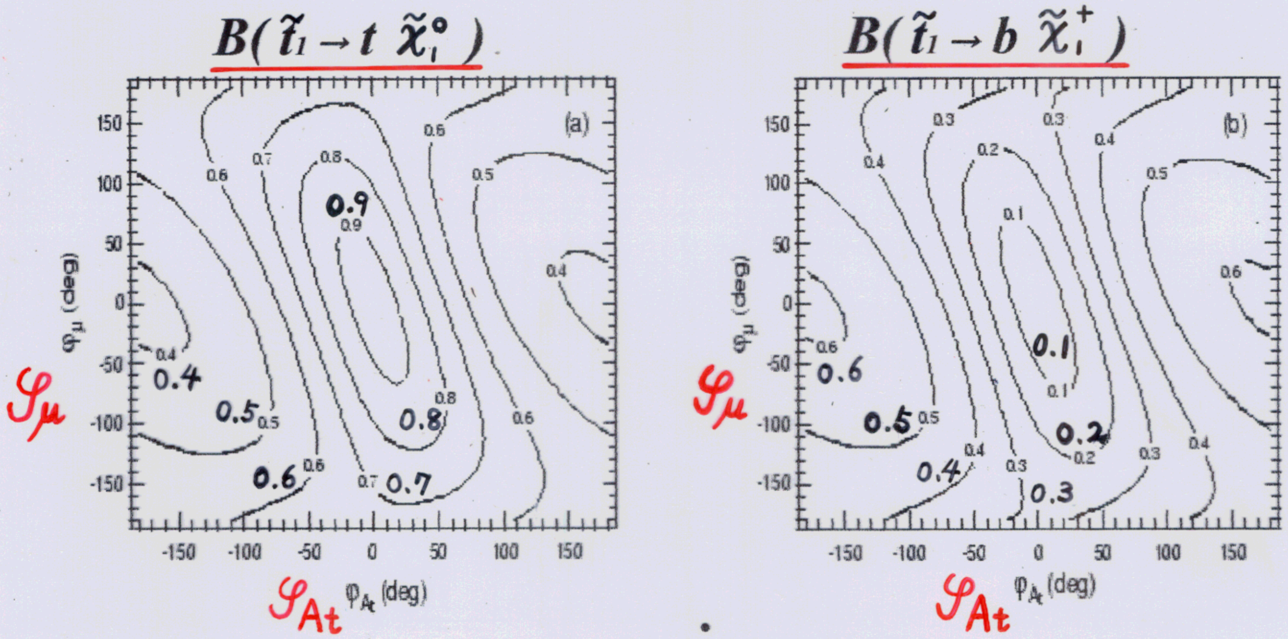


Figure 2: Contours of the $\tilde{t}_1$ decay branching ratios $B(\tilde{t}_1 \to t\tilde{\chi}_1^0)$ (a) and $B(\tilde{t}_1 \to b\tilde{\chi}_1^+)$ (b) in the φ_{A_t}-φ_μ plane for $\tan\beta = 8$, $(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1})$= (400,700,200) GeV, $|A| = 800$ GeV, $|\mu| = 500$ GeV, $\varphi_{A_b} = \varphi_1 = 0$, and $m_{H^+} = 600$ GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$.

$|A_t| = |A_b| = |A|$, $M_2 = 300$GeV

$\Downarrow$

The $\tilde{t}_1$ decay branching ratios can depend on the phases (φ_{A_t}, φ_μ) quite strongly !

(iv) Results on $\tilde{b}_1$ decays;

-- φ_{A_b} dependence;

$B(\tilde{b}_1 \to X)$

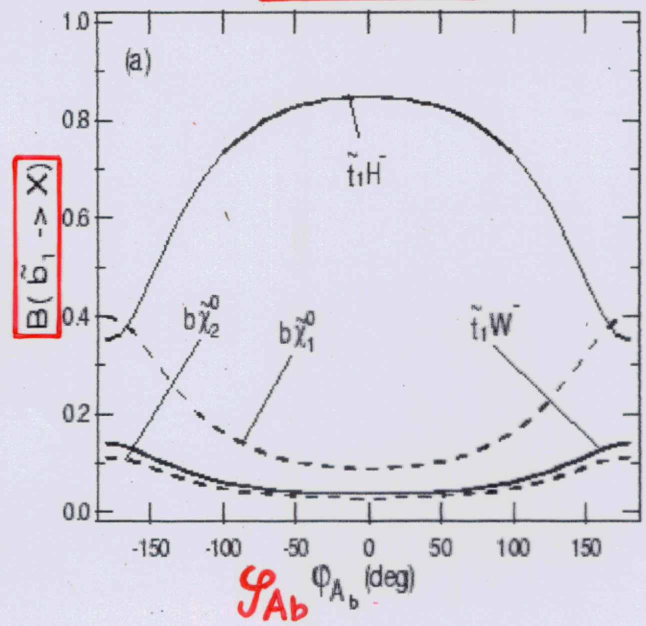


Figure 5: φ_{A_b} dependence of the $\tilde{b}_1$ (a) [$\tilde{b}_2$ (b)] decay branching ratios for $\tan\beta$=30, $(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_L})$= (200,700,400) GeV [(175,500,350) GeV], $(|A|, |\mu|)$=(800,700) GeV [(600,500) GeV], $\varphi_{A_t}=\varphi_\mu=\pi$, φ_1=0, and m_{H^+} = 180 GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$.

|A_t|=|A_b|=|A| , M_2=300GeV

$\Downarrow$

The $\tilde{b}_1$ decay branching ratios can be very sensitive to the phase φ_{Ab}!

(v) Results on $\tilde{t}_2$ decays;

-- φ_{A_t} dependence;

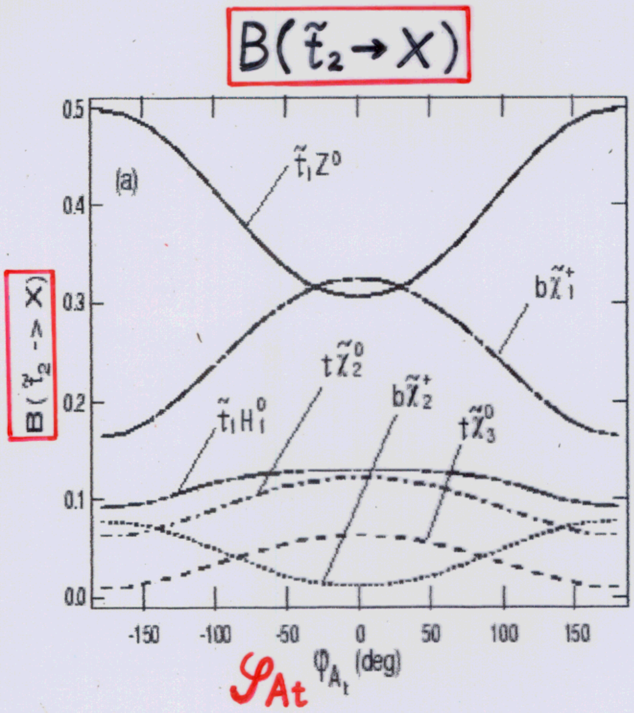


Figure 4: φ_{A_t} dependence of the $\tilde{t}_2$ decay branching ratios for $\varphi_\mu = 0$ (a) and $\pi/2$ (b) with $\tan\beta=8$, $(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1})=(400,700,200)$ GeV, $|A| = 800$ GeV, $|\mu| = 500$ GeV, $\varphi_{A_b}=\varphi_1=0$, and $m_{H^+} = 600$ GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$. Note that the $\tilde{t}_1 H^0_{2,3}$ and $\tilde{b}_1 H^+$ modes are kinematically forbidden here.

$|A_t| = |A_b| = |A|$, $M_2 = 300GeV$

$\Downarrow$

The $\tilde{t}_2$ decay branching ratios can be very sensitive to the phase φ_{At}!

(v) Results on $\tilde{b}_2$ decays;

– φ_{A_b} dependence;

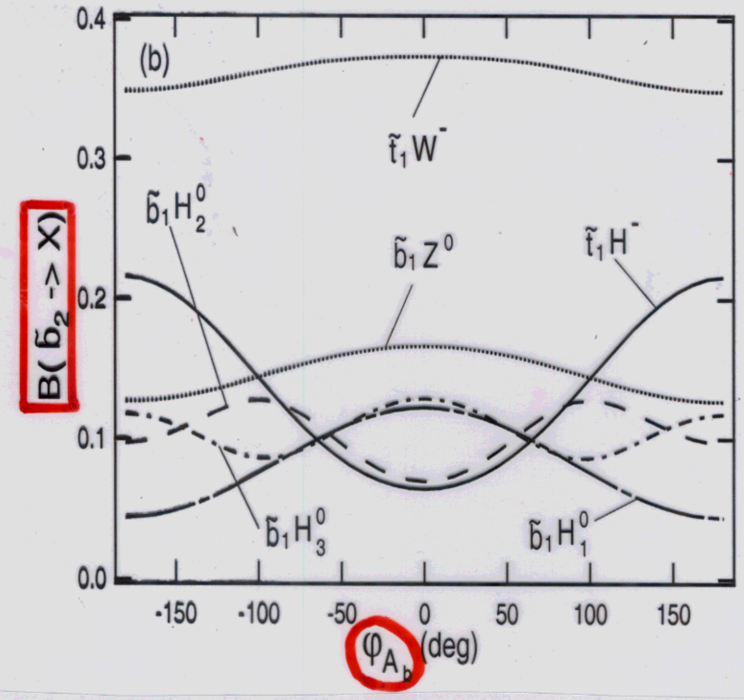


Figure 5: φ_{A_b} dependence of the $\tilde{b}_1$ (a) [$\tilde{b}_2$ (b)] decay branching ratios for $\tan\beta$=30, ($m_{\tilde{t}_1}$,$m_{\tilde{t}_2}$,$m_{\tilde{b}_1}$)= (200,700,400) GeV [(175,500,350) GeV], (|A|, |μ|)=(800,700) GeV [(600,500) GeV], φ_{A_t}=φ_μ=π, φ_1=0, and m_{H^+} = 180 GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$. Only interesting modes are shown in Fig.b where we have $m_{\tilde{b}_2} \sim$ 570GeV and ($m_{H_1^0}$,$m_{H_2^0}$,$m_{H_3^0}$) $\sim$ (114,156,158) GeV.

$|A_t| = |A_b| = |A|$, $M_2 = 300GeV$

⇓

(**The $\tilde{b}_2$ decay branching ratios can be very sensitive to the phase φ_{A_b}!**)

(vi) Impact of CP phases;

-- The CP phases can significantly affect not only CP-violating observables (such as the lepton EDM) but also CP-conserving quantities (such as the branching ratios of the $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays).

-- Hence the possible sizable phases could have important consequences for the determination of the basic MSSM-parameters from measurements of the observables, since almost none of the basic MSSM-parameters are directly measured.

5 Impact of CP phases on the MSSM parameter determination

-- Observables (such as masses, cross sections & branching ratios) are functions of the basic MSSM-Parameters.

$$\begin{cases} O_1 = O_1(P_1, \ldots, P_n) \\ \vdots \\ O_N = O_N(P_1, \ldots, P_n) \end{cases} \qquad (N > n)$$

$\{ O_1, \ldots, O_N \} = \{$ masses, cross sections, branching ratios$\}$

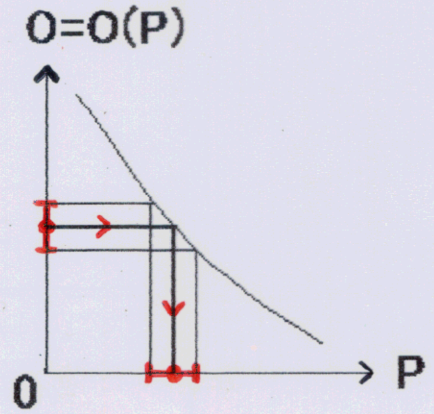
$\{ P_1, \ldots, P_n \} = \{ \tan\beta, M_2, M_1, \mu, A_{t,b}, \ldots \}$

-- These observables $\{ O_1, \ldots, O_N \}$ over-constrain the basic MSSM-parameters $\{ P_1, \ldots, P_n \}$!

-- *So, we can determine these parameters $\{P_j\}$ and their errors $\{\Delta P_j\}$ by a χ^2-fit to the experimental data of these observables $\{O_i \pm \Delta O_i\}$.*

$O_i = O_i(P_j)$ *($\{O_i\}$ over-constrain $\{P_j\}$)*

$\{O_i \pm \Delta O_i\} \rightarrow \{P_j \pm \Delta P_j\}$ *(by a χ^2-fit)*



-- ***If these parameters $\{P_j\}$ are actually complex, then real parameter fit would result in a totally wrong MSSM parameter determination !***

● Example of Impact - a case study;

(i) Assumptions;

We assume the following situation:

(1) At LHC;

$m_{\tilde{g}}$ ***can be measured with 3% error.***

(pri. com. with A. De Roeck)

(2) At TESLA (GLC) $(\sqrt{s} < 1\ TeV)$;

- $m_{\tilde{\chi}_i^+}$, $m_{\tilde{\chi}_j^0}$, $m_{H_1^0}$ ***can be measured with high accuracy.***

  (e.g. $\Delta m_{\tilde{\chi}_1^+} = 0.2$ GeV, $\Delta m_{\tilde{\chi}_1^0} = 0.3$ GeV, $\Delta m_{H_1^0} = 0.05$ GeV)
- $m_{H_2^0}$, $m_{H_3^0}$, m_{H^+} ($\lesssim$500GeV) ***can with error of 1.5GeV.***
- $m_{\tilde{t}_{1,2}}$, $m_{\tilde{b}_{1,2}}$ ($\lesssim$500GeV) ***can with 1% error.***

TESLA (TDR), hep-ph/0106315;
E. Accomando et al., Phys.Rep.229(1998)1;
H.Martyn, G.Blair, hep-ph/9910416

(3) At CLIC ($\sqrt{s}$ = 2 TeV e+e- Collider);

- $m_{H_2^0}$, $m_{H_3^0}$, m_{H^+} *(>500GeV) can be measured with 1% error.*
- $m_{\tilde{t}_{1,2}}$, $m_{\tilde{b}_{1,2}}$ *(>500GeV) can ... with 3% error.*

(pri. com. with A. De Roeck & M. Battaglia)

- *We can get e- & e+ beam helicity-polarizations of P(e-) = 80% & P(e+) = 40%.*

(Note) We do not take into account additional information from LHC on $\tilde{t}$ and $\tilde{b}$ systems because the amount of information available strongly depends on the scenario realized in nature.

(pri. com. with G. Polesello)

(ii) Strategy;

Our strategy is as follows:

(Step 1) Take a specific set of values of the basic MSSM-parameters:

$\{ \tan\beta, M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}}, |A_t|, |A_b|, \varphi_{A_t}, \varphi_{A_b}, \varphi_1, M_2, |\mu|, \varphi_\mu, m_{\tilde{g}}, m_{H^+} \}$

(Step 2) Calculate the observables:

- ***masses of*** $\tilde{t}_i, \tilde{b}_i, \tilde{\chi}^0_j, \tilde{\chi}^+_k, H^0_i$
- ***production cross sections of*** $e^+_{\uparrow} e^-_{\uparrow} \to \tilde{t}_i \bar{\tilde{t}}_j$ ***&*** $\tilde{b}_i \bar{\tilde{b}}_j$
- ***branching ratios of*** $\tilde{t}_i$ ***&*** $\tilde{b}_i$ ***decays***

(Step 3) Regard these calculated values of the observables as real "experimental data" with definite errors.

(Note) For the cross sections & branching ratios, we take only statistical errors for $L=1ab^{-1}$ ***at*** $\sqrt{s}=2TeV$ ***(at CLIC). We have doubled these statistical errors for safety.***

(Step 4) Determine the basic MSSM-parameters and their errors by a χ^2***-fit to the "experimental data".***

(iii) Scenarios; (STEP 1)

We consider 2 typical scenarios:

- $\boxed{\textit{Small } \tan\beta \textit{ (=6) scenario}}$;

The basic MSSM-parameters:

$\tan\beta = 6$,
$(M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}}) = (623, 409, 107)$ GeV,
$|A_t| = |A_b| = 800$ GeV,
$\varphi_{A_t} = \varphi_{A_b} = \pi/4$, $\varphi_1 = 0$,
$M_2 = 300$ GeV, $\mu = -350$ GeV,
$m_{\tilde{g}} = 1000$ GeV, $m_{H^+} = 900$ GeV

- $\boxed{\textit{Large } \tan\beta \textit{ (=30) scenario}}$;

The basic MSSM-parameters:

$\tan\beta = 30$,
$(M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}}) = (692, 198, 360)$ GeV,
$|A_t| = 600$ GeV, $|A_b| = 1000$ GeV,
$\varphi_{A_t} = \pi/4$, $\varphi_{A_b} = 3\pi/2$, $\varphi_1 = 0$,
$M_2 = 200$ GeV, $\mu = -350$ GeV,
$m_{\tilde{g}} = 1000$ GeV, $m_{H^+} = 350$ GeV

($\rightarrow$ For the calculated branching ratios, see Table.1.)

(STEP 2) & (STEP 3)

Calculated Masses with assumed errors :

- ***Small tanβ (=6) scenario;***

$m_{\tilde{t}_1} = (350 \pm 3.5)$ GeV, $m_{\tilde{t}_2} = (700 \pm 21)$ GeV,

$m_{\tilde{b}_1} = (170 \pm 1.7)$ GeV, $m_{\tilde{b}_2} = (626 \pm 19)$ GeV,

...

- ***Large tanβ (=30) scenario;***

$m_{\tilde{t}_1} = (210 \pm 2.1)$ GeV, $m_{\tilde{t}_2} = (729 \pm 22)$ GeV,

$m_{\tilde{b}_1} = (350 \pm 3.5)$ GeV, $m_{\tilde{b}_2} = (700 \pm 21)$ GeV,

...

Calculated cross sections of $e^-_{\uparrow} e^+_{\uparrow} \rightarrow \tilde{t}_i \bar{\tilde{t}}_j$ & $\tilde{b}_i \bar{\tilde{b}}_j$:

tan(beta)= 6 scenario

cross sections (ab): (at $\sqrt{s} = 2$ TeV(CLIC))

(P(e-),P(e+))	(0.8,-0.4)	(-0.8,0.4)
(stop_1 stop_1)	6003	11861
(stop_1 stop_2)	987	738
(stop_2 stop_1)	987	738
(stop_2 stop_2)	11263	1390
(sbot_1 sbot_1)	1290	4378
(sbot_1 sbot_2)	5	4
(sbot_2 sbot_1)	5	4
(sbot_2 sbot_2)	11009	1063

tan(beta)= 30 scenario

cross sections (ab): (at $\sqrt{s} = 2$ TeV(CLIC))

(P(e-),P(e+))	(0.8,-0.4)	(-0.8,0.4)
(stop_1 stop_1)	1151	16177
(stop_1 stop_2)	334	249
(stop_2 stop_1)	334	249
(stop_2 stop_2)	10570	950
(sbot_1 sbot_1)	1152	3678
(sbot_1 sbot_2)	67	50
(sbot_2 sbot_1)	67	50
(sbot_2 sbot_2)	8352	793

(with doubled statistical errors for $L = 1\ ab^{-1}$ at $\sqrt{s} = 2$ TeV (at CLIC))

(Table.1) Calculated branching ratios:

Table 1: Decay branching ratios (in %) for top squarks and bottom squarks in the two considered scenarios. Corresponding values of the underlying MSSM parameters are given in the text.

	scenario with $\tan\beta = 6$				scenario with $\tan\beta = 30$			
channel	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
$q\tilde{\chi}_1^0$	66.4	1.6	100	0.6	0	0.6	63.5	0.6
$q\tilde{\chi}_2^0$	0	7.5	0	8.7	0	8.5	36.1	10.3
$q\tilde{\chi}_3^0$	0	13.1	0	0.3	0	11.1	0	4.6
$q\tilde{\chi}_4^0$	0	6.6	0	2.4	0	8.7	0	4.6
$q'\tilde{\chi}_1^\pm$	33.1	19.2	0	9.7	100	22.5	0	14.1
$q'\tilde{\chi}_2^\pm$	0	1.6	0	21.0	0	6.8	0	24.2
$W^\pm\tilde{q}'_1$	0.5	0.3	0	56.8	0	3.1	0.4	27.1
$H^\pm\tilde{q}'_1$	0	0	0	0	0	7.7	0	6.4
$Z\tilde{q}_1$	–	26.9	–	0.2	–	13.1	–	1.5
$H_1\tilde{q}_1$	–	23.4	–	0.2	–	12.7	–	1.4
$H_2\tilde{q}_1$	–	0	–	0	–	2.8	–	2.7
$H_3\tilde{q}_1$	–	0	–	0	–	2.4	–	2.7

(with doubled statistical errors
for $L = 1\ ab^{-1}$ at $\sqrt{s} = 2$ TeV (at CLIC))

(iv) Results of χ^2-fit ; (STEP 4)

We determine the basic MSSM-parameters and their errors by a χ^2-fit to the "experimental data" of the observables:

(Results of χ^2-fit)

Table 2: Extracted parameters from the "experimental data" of the masses, production cross sections and decay branching ratios of $\tilde{t}_i$ and $\tilde{b}_i$. The original parameters for each scenario are given in the text.

scenario	$\tan\beta = 6$ scenario	$\tan\beta = 30$ scenario
$M^2_{\tilde{D}}$	$(2.88 \pm 0.06) \times 10^4$	$(1.30 \pm 0.02) \times 10^5$
$M^2_{\tilde{U}}$	$(1.67 \pm 0.04) \times 10^5$	$(3.93 \pm 0.12) \times 10^4$
$M^2_{\tilde{Q}}$	$(3.88 \pm 0.04) \times 10^5$	$(4.79 \pm 0.04) \times 10^5$
$\mathrm{Re}(A_t)$	565.0 ± 13.0	424.0 ± 14.0
$\mathrm{Im}(A_t)$	$\pm 566.0 \pm 14.0$	$\pm 425.0 \pm 15.0$
$\mathrm{Re}(A_b)$	620.0 ± 190.0	6.5 ± 420.0
$\mathrm{Im}(A_b)$	$\pm 230.0 \pm 580.0$	$\pm 999.0 \pm 52.0$
$\mathrm{Re}(M_1)$	149.3 ± 0.3	99.6 ± 0.6
$\mathrm{Im}(M_1)$	1.0 ± 1.5	-0.5 ± 2.8
M_2	300.0 ± 0.4	200.0 ± 0.5
$\mathrm{Re}(\mu)$	-350.0 ± 0.3	-350.0 ± 0.6
$\mathrm{Im}(\mu)$	-0.02 ± 0.9	1.5 ± 5.0
$\tan\beta$	6.0 ± 0.2	30.0 ± 0.8
$m_{\tilde{g}}$	1000.0 ± 30	1000.0 ± 30
$m_{H^\pm}$	900.0 ± 5.0	350.0 ± 0.8

(Note) ***The sign ambiguity for Im parts of the parameters is due to the fact that we consider CP-even observables. This ambiguity can be resolved by considering appropriate CP-odd observables in the analysis.***

See Aoki-Oshimo, Mod.Phys.Lett. A13(1998)3225;
Yang-Du, P.R.D65(2002)115005;
Bartl et al., hep-ph/0202198 & hep-ph/0306304

↓

All parameters except A_b can be determined rather precisely:

$\tan\beta$	*with 3% error*
$M_{\tilde{Q}}$, $M_{\tilde{U}}$, $M_{\tilde{D}}$	*with 1% to 2% errors*
A_t	*with 2% to 3% error*
A_b	*with 50% error*

(Note) The reason why the error of A_b is so large:

Sbottom masses and mixing angle are rather insensitive to A_b due to small m_b (=5GeV). So, the observables are rather insensitive to A_b. This leads to the large error of A_b.

(Note) Real parameter fit;

The χ^2-fit by using only real parameters results in a much larger χ^2 value ! :

$$\Delta\chi^2 \equiv \chi^2(\text{real para. fit}) - \chi^2(\text{complex para. fit})$$

$\Delta\chi^2 = 287$, DOF= 61 (for $\tan\beta=6$ scenario)

$\Delta\chi^2 = 23$, DOF= 61 (for $\tan\beta=30$ scenario)

(Result of Real Parameter Fit)

scenario	$\tan\beta = 6$ scenario	$\tan\beta = 30$ scenario
$M^2_{\tilde{D}}$	(2.879 ± 0.059) x 10^4	(1.311 ± 0.021) x 10^5
$M^2_{\tilde{U}}$	(1.501 ± 0.028) x 10^5	(3.938 ± 0.12) x 10^4
$M^2_{\tilde{Q}}$	(4.022 ± 0.041) x 10^5	(4.802 ± 0.038) x 10^5
$\mathrm{Re}(A_t)$	606.3 ± 8.6	600.4 ± 9.0
$\mathrm{Im}(A_t)$	0	0
$\mathrm{Re}(A_b)$	644.4 ± 210	1016 ± 58
$\mathrm{Im}(A_b)$	0	0
$\mathrm{Re}(M_1)$	149.6 ± 0.31	99.55 ± 0.62
$\mathrm{Im}(M_1)$	0	0
M_2	301.1 ± 0.38	199.9 ± 0.47
$\mathrm{Re}(\mu)$	-349.5 ± 0.25	-350.0 ± 0.64
$\mathrm{Im}(\mu)$	0	0
$\tan\beta$	6.399 ± 0.14	29.20 ± 0.63
$m_{\tilde{g}}$	1000.0 ± 30	1000.0 ± 30
m_{H^+}	900.0 ± 5.2	351.0 ± 0.85
χ^2	286.6	22.5

$\Downarrow$

(Real parameter fit results in a totally wrong MSSM parameter determination!)

6 Conclusion

-- *We have shown that the effect of the CP phases of the complex parameters $A_{t,b}$, μ and M_1 on the branching ratios of the $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays can be quite strong in a significant portion of the MSSM parameter space.*

-- *This could have an important impact on*

(i) the search for $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$,

and

(ii) the determination of the basic MSSM-parameters

at future colliders such as LC & LHC.