

CP asymmetries in charged Higgs boson decays in MSSM

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*Contribution to the 4th workshop "Gravity, Astrophysics, and Strings at the Black Sea",
Primorsko, June 10-16, 2007*

Abstract

In the Standard Model with Minimal Supersymmetry, the Lagrangian contains complex parameters which lead to additional CP violation. We study CP violating asymmetries in the decays of the MSSM charged Higgs boson H^\pm , induced by loop corrections with intermediate SUSY particles, and perform analytical and numerical analysis. The decay rate asymmetry can go up to 25% and the forward-backward asymmetry can reach up to 10%.

The CP-symmetry is broken in nature and this feature makes it an important tool for testing fundamental theories. An understanding of its non-conservation in particle physics may provide essential information about the mechanism, causing the dominance of the matter over antimatter in the observable universe. Generally, effects of CP-violation originate in non vanishing complex phases in the Lagrangian of the theory. In particular, in the Minimal Supersymmetric Standard Model (MSSM), the Higgs mixing parameter μ in the superpotential, the U(1) and SU(2) gaugino mass parameters M_1 and M_2 , and the trilinear couplings A_f (corresponding to a fermion f) can have physical phases which cannot be rotated away without introducing phases in other couplings [1]. The experimental upper bounds on the electron and neutron electric dipole moments (EDMs) constrain the phase of μ , $\phi_\mu < \mathcal{O}(10^{-2})$ [2] for a typical SUSY mass scale of the order of a few hundred GeV, however the phases of the other parameters mentioned above are practically unconstrained. The CP-violating effects that might arise from the trilinear couplings of the first generation $A_{u,d}$ are relatively small, as they are proportional to $m_{u,d}$. However, the trilinear couplings of the third generation $A_{t,b,\tau}$ can lead to significant effects of CP-violation, especially in top quark physics [3].

In the following, we study CP violation in the decays of the charged Higgs bosons H^\pm within the MSSM. At tree level, there are three possible decay modes of H^+ into ordinary particles: $H^+ \rightarrow t\bar{b}$, $H^+ \rightarrow \nu\tau^+$ and $H^+ \rightarrow W^+h^0$, where h^0 is the lightest neutral Higgs boson. Loop corrections due to a Lagrangian with complex parameters lead to non zero decay rate asymmetry between the partial decay widths of H^+ and H^- ,

$$\delta^{CP} = \frac{\Gamma(H^+ \rightarrow \dots) - \Gamma(H^- \rightarrow \dots)}{\Gamma(H^+ \rightarrow \dots) + \Gamma(H^- \rightarrow \dots)}, \quad (1)$$

and that would be a clear signal of CP violation. We consider such decay rate asymmetries in MSSM with complex parameters for the quark decay mode $H^+ \rightarrow t\bar{b}$ – the asymmetry $\delta_{t\bar{b}}^{CP}$ [4], and for the bosonic decay mode $H^+ \rightarrow W^+h^0$ [5] – the asymmetry $\delta_{Wh^0}^{CP}$. For the quark decay mode $H^+ \rightarrow t\bar{b}$ we go a step further by including the decay products of the top quark. This allows to examine CP-violating asymmetries due to the polarization of the top quark [6]. The top-quark decays before forming a bound state due to its large

mass, so that the polarization can be measured by the angular distributions of its decay products. Moreover, the polarization is very sensitive to CP violation. The considered CP violating forward-backward (FB) and energy asymmetries are constructed by using angular or energy distributions of the decay particles, following the formalism of [7]. This talk is entirely based on the results of [5] and [6].

We study the following processes, related to the quark decay mode of H^\pm [6] (See Fig. 1)

$$\begin{aligned} H^+ &\rightarrow \bar{b}t \rightarrow \bar{b}b'W^+, \\ H^- &\rightarrow b\bar{t} \rightarrow b\bar{b}'W^-, \end{aligned} \quad (2)$$

and

$$\begin{aligned} H^+ &\rightarrow \bar{b}t \rightarrow \bar{b}b'W^+ \rightarrow \bar{b}b'l^+\nu_l, \\ H^- &\rightarrow b\bar{t} \rightarrow b\bar{b}'W^- \rightarrow b\bar{b}'l^-\bar{\nu}_l. \end{aligned} \quad (3)$$

The CP-violation is induced by SUSY loop corrections in the $H^\pm tb$ -vertices, whose

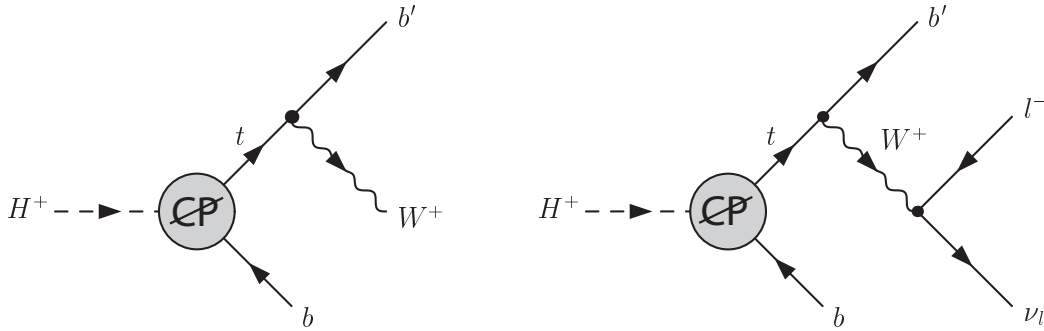


Figure 1: The Feynman graphs of the processes we study.

effective amplitudes are given by

$$\mathcal{M}_{H^+} = i\bar{u}(p_t)[Y_b^+ P_R + Y_t^+ P_L]u(-p_{\bar{b}}) \quad (4)$$

$$\mathcal{M}_{H^-} = i\bar{u}(p_b)[Y_t^- P_R + Y_b^- P_L]u(-p_{\bar{t}}), \quad (5)$$

The one loop diagrams that contribute are shown on Fig. 2. The Yukawa couplings Y_i^\pm ($i = t, b$) are a sum of the tree-level couplings y_t and y_b , and the contributions from the loops – δY_i^\pm ($i = t, b$):

$$Y_i^\pm = y_i + \delta Y_i^\pm \quad i = t, b. \quad (6)$$

The loop contributions δY_i^\pm have, in general, both CP-invariant and CP-violating parts:

$$\delta Y_i^\pm = \delta Y_i^{inv} \pm \frac{1}{2} \delta Y_i^{CP}. \quad (7)$$

In addition, both CP-invariant and CP-violating parts have real and imaginary (absorptive) parts. Only the real parts $\text{Re} \delta Y_{t,b}^{CP}$ enter the CP-violating asymmetries. We examine the following CP-violating asymmetries related to the processes (2) and (3):

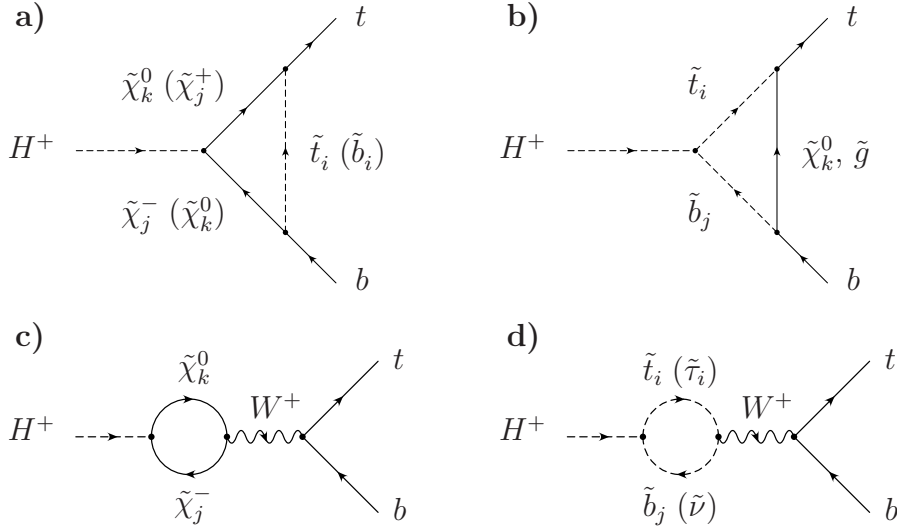


Figure 2: Sources for CP violation in $H^+ \rightarrow t\bar{b}$ decays at 1-loop level in the MSSM with complex couplings ($i, j = 1, 2; k = 1, \dots, 4$).

- **CP-violating decay rate asymmetry δ^{CP}** , defined as

$$\delta_f^{CP} = \frac{N_f - N_{\bar{f}}}{N_f + N_{\bar{f}}}, \quad f = b', l^\pm \quad (8)$$

where $N_{f, \bar{f}}$ is the total number of particles $f(\bar{f})$ in (2) or (3) respectively.

- **CP-violating forward-backward (FB) asymmetry $\Delta A_{b(l)}^{CP}$** , which we construct from the FB asymmetries $A_{f, \pm}^{FB}$ of the processes (2) and (3) using the angular distributions of the fermions $f = b', l^\pm$ from the top quark decay in (2) and (3). This asymmetry is defined as

$$\Delta A_f^{CP} = A_{f+}^{FB} - A_{f-}^{FB}, \quad (9)$$

where A_{\pm}^{FB} are the ordinary FB asymmetries of the processes

$$A_{f, \pm}^{FB} = \frac{\Gamma_{f, \pm}^F - \Gamma_{f, \pm}^B}{\Gamma_{f, \pm}^F + \Gamma_{f, \pm}^B}, \quad (10)$$

and we have

$$\Gamma_{\pm}^F = \int_0^{\frac{\pi}{2}} \frac{d\Gamma^\pm}{d\cos\theta} d\cos\theta, \quad \Gamma_{\pm}^B = \int_{\frac{\pi}{2}}^{\pi} \frac{d\Gamma^\pm}{d\cos\theta} d\cos\theta, \quad (11)$$

i.e. $\Gamma_{f, \pm}^F$ are the number of particles $f(\bar{f})$ measured in the forward direction of the decaying $t(\bar{t})$ quarks and $\Gamma_{f, \pm}^B$ are the number of $f(\bar{f})$ measured in the backward direction of the decaying $t(\bar{t})$ quarks.

- **CP-violating energy asymmetry ΔR_b^{CP}** can be defined analogously, using the energy distributions of the processes (2) and (3), namely

$$\Delta R_b^{CP} = R_{b+} - R_{b-}, \quad (12)$$

where R_{\pm} are given by

$$R_{b,\pm} = \frac{\Gamma_{\pm}(x > x_0) - \Gamma_{\pm}(x < x_0)}{\Gamma_{\pm}(x > x_0) + \Gamma_{\pm}(x < x_0)}, \quad (13)$$

x is a dimensionless variable proportional to the energy, $x = E_b/m_{H^+}$ and x_0 is any fixed value in the energy interval.

The analytical results for the asymmetries are rather simple:

$$\delta_b^{CP} = \delta_l^{CP} = \frac{\Gamma^{CP}}{\Gamma^{inv}}, \quad (14)$$

$$\Delta A_{b(l)}^{CP} = 2\alpha_{b(l)} m_t^2 m_H^2 \frac{m_H^2 - m_t^2}{(m_H^2 + m_t^2)^2} \mathcal{P}^{CP}, \quad (15)$$

$$\Delta R_b^{CP} = \frac{1}{2} \alpha_b (m_H^2 - m_t^2) \mathcal{P}^{CP}, \quad (16)$$

where Γ^{CP} and \mathcal{P}^{CP} are two linear combinations of the two formfactors:

$$\Gamma^{CP} = [y_t \text{Re}(\delta Y_t^{CP}) + (y_b \text{Re}(\delta Y_b^{CP}))] (p_t p_{\bar{b}}) - m_t m_b [y_t \text{Re}(\delta Y_b^{CP}) + y_b \text{Re}(\delta Y_t^{CP})], \quad (17)$$

$$\mathcal{P}^{CP} = \frac{y_t \text{Re}(\delta Y_t^{CP}) - y_b \text{Re}(\delta Y_b^{CP})}{(y_t^2 + y_b^2)(p_t p_{\bar{b}}) - 2m_t m_b y_t y_b}. \quad (18)$$

Here Γ^{CP} is the CP-violating part of the relevant H^{\pm} partial decay rate and \mathcal{P}^{CP} is the CP-violating part of the polarization of the top-quark. The coefficient $\alpha_{b(l)}$ determines the sensitivity of the b-quark (lepton) to the polarization of the top quark:

$$\alpha_b = \frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2}, \quad \alpha_l = 1. \quad (19)$$

Further analysis on the results shows that one does not need to explore numerically all of these asymmetries, as some of them are connected. In this context we reduce the numerical analysis on the following argumentation:

- All of the discussed asymmetries are linear combinations of the CP-violating form factors $\text{Re}(\delta Y_t^{CP})$ and $\text{Re}(\delta Y_b^{CP})$, through a dependance on \mathcal{P}^{CP} (18) or Γ^{CP} (17). In order to measure these formfactors, one needs to measure: **1**) the decay rate asymmetries $\delta_{b,l}^{CP}$ which are proportional to Γ^{CP} and **2**) the angular and / or energy asymmetries which are proportional to \mathcal{P}^{CP} for a given process.
- As there is no CP violation in $t \rightarrow bW$, the decay rate asymmetries in $H^{\pm} \rightarrow W^{\pm} b b'$ and $H^{\pm} \rightarrow b b' l^{\pm} \nu$ are equal to the decay rate asymmetry in $H^{\pm} \rightarrow t b$. We denote it, following [4], by δ^{CP} :

$$\delta^{CP} = \delta_b^{CP} = \delta_l^{CP} = \frac{\Gamma^{CP}}{\Gamma^{inv}}. \quad \delta^{CP} = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}, \quad (20)$$

where Γ^{\pm} is the partial decay rate of the process $H^{\pm} \rightarrow t b$

- The angular and energy asymmetries – $\Delta A_{b,l}^{CP}$ and ΔR_b^{CP} , are not independent either. The angular asymmetries for the b -quarks and the leptons are related by

$$\Delta A_l^{CP} = \frac{\alpha_l}{\alpha_b} \Delta A_b^{CP} \approx 2.6 \Delta A_b^{CP}. \quad (21)$$

Furthermore, there is a simple relation between the b -quark energy and angular asymmetries:

$$\Delta R_b^{CP} = \frac{(m_{H^+}^2 + m_t^2)^2}{4 m_{H^+}^2 m_t^2} \Delta A_b^{CP}, \quad (22)$$

which implies that for $m_{H^+} > m_t$, ΔR_b^{CP} is bigger than ΔA_b^{CP} . Thus, in general, ΔR_b^{CP} is the biggest asymmetry of those defined through the polarization of the top quark for $m_{H^+} > 490$ GeV.

In the following, we present numerical results only on the decay rate asymmetry δ^{CP} and on the energy asymmetry ΔR_b^{CP} .

In order not to vary too many parameters we fix a part of the parameter space by the choice:

$$\begin{aligned} M_2 = 300 \text{ GeV}, \quad M_3 = 745 \text{ GeV}, \quad M_{\tilde{U}} = M_{\tilde{Q}} = M_{\tilde{D}} = M_E = M_L = 350 \text{ GeV}, \\ \mu = -700 \text{ GeV}, \quad |A_t| = |A_b| = |A_\tau| = 700 \text{ GeV}. \end{aligned} \quad (23)$$

According to the experimental limits on the electric and neutron EDM's, we take $\phi_\mu = 0$ or $\phi_\mu = \pi/10$. The remaining CP-violating phases we vary, are the phases of A_t , A_b and A_τ . In the numerical code we use running top and bottom Yukawa couplings, calculated at the scale $Q = m_{H^+}$. Fig. 3a and Fig. 3b show the asymmetries δ^{CP} and ΔR_b^{CP} as functions of m_{H^+} for $\phi_{A_t} = \pi/2$, $\phi_{A_b} = 0$ and $\phi_\mu = 0$. (Our studies have shown that the most important CP-violating phase is ϕ_{A_t} . There is only a very weak dependence on ϕ_{A_b} and ϕ_{A_τ} and therefore we take them zero.) For $\tan \beta = 5$ the decay rate asymmetry δ^{CP} goes up to 20%, while ΔR_b^{CP} reaches 8% for the same values of the parameters. The asymmetries strongly depend on $\tan \beta$ and they quickly decrease as $\tan \beta$ increases. For $m_{H^+} < m_{\tilde{t}_1} + m_{\tilde{b}_1}$, the asymmetries are very small. The main contributions to both δ^{CP} and ΔR_b^{CP} come from the self-energy graph with stop-sbottom. The vertex graph with stop-sbottom-gluino also gives a relatively large contribution. The contributions of these two graphs in δ^{CP} and ΔR_b^{CP} are shown in Fig. 4a and Fig. 4b. The contribution of the rest of the graphs is negligible.

Further, we take a very small phase, $\phi_\mu = \pi/10$, in order to fit with the experimental data. As can be seen in Fig. 5a and Fig. 5b, the asymmetries can increase up to 25% for δ^{CP} and 10% for ΔR_b^{CP} , respectively. The discussed asymmetries δ^{CP} and ΔR_b^{CP} shows a very strong dependence on the sign of μ . As noted above, our analysis is done for $\mu = -700$ (see (23)), however if μ changes sign, $\mu = 700$, all asymmetries become extremely small.

We now turn to the bosonic decay mode of the charged Higgs boson $H^+ \rightarrow W^+ h^0$. We are interested again in the CP violation caused by SUSY loop corrections in the $H^\pm W h^0$ -vertex and study the decay rate asymmetry between the charge conjugate processes $H^+ \rightarrow$

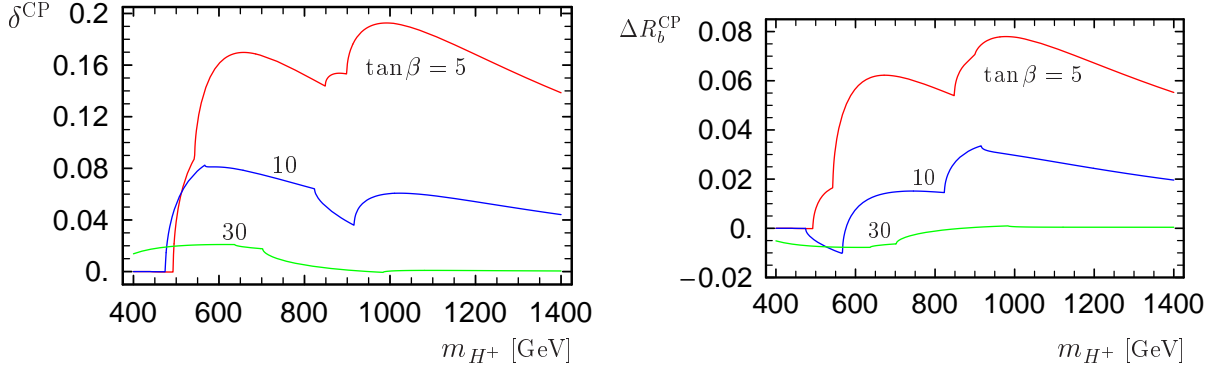


Figure 3: The asymmetries δ^{CP} and ΔR_b^{CP} as functions of m_{H^+} for $\phi_{A_t} = \pi/2$, $\phi_{A_b} = \phi_\mu = 0$. The red, blue, and green lines are for $\tan\beta = 5, 10,$ and 30 .

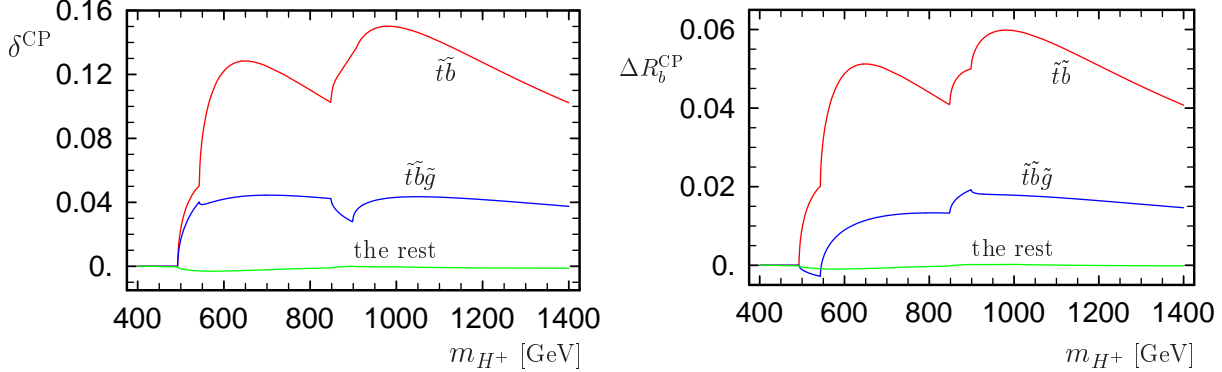


Figure 4: The contribution of the $\tilde{t}\tilde{b}$ self-energy (red line), $\tilde{t}\tilde{b}\tilde{g}$ vertex contribution (blue line) and the sum of the other (green line) diagrams to δ^{CP} and ΔR_b^{CP} as functions of m_{H^+} for $\tan\beta = 5$ and $\phi_{A_t} = \pi/2$, $\phi_{A_b} = \phi_\mu = 0$.

W^+h^0 and $H^- \rightarrow W^-h^0$:

$$\delta_{Wh^0}^{CP} = \frac{\Gamma(H^+ \rightarrow W^+h^0) - \Gamma(H^- \rightarrow W^-h^0)}{\Gamma(H^+ \rightarrow W^+h^0) + \Gamma(H^- \rightarrow W^-h^0)}. \quad (24)$$

The matrix elements of $H^+ \rightarrow W^+h^0$ and $H^- \rightarrow W^-h^0$ are given by

$$M_{H^\pm} = ig\varepsilon_\alpha^\lambda(p_W)p_h^\alpha Y^\pm, \quad (25)$$

where $\varepsilon_\alpha^\lambda(p_W)$ is the polarization vector of W^\pm , Y^\pm are the loop corrected couplings. The CP-violating asymmetry $\delta_{Wh^0}^{CP}$ is determined by the real parts $\text{Re}(\delta Y_k^{CP})$:

$$\delta Y_k^{CP} = \text{Re}(\delta Y_k^{CP}) + i \text{Im}(\delta Y_k^{CP}), \quad \delta_{Wh^0}^{CP} \simeq \frac{2 \sum_k \text{Re}(\delta Y_k^{CP})}{y}, \quad (26)$$

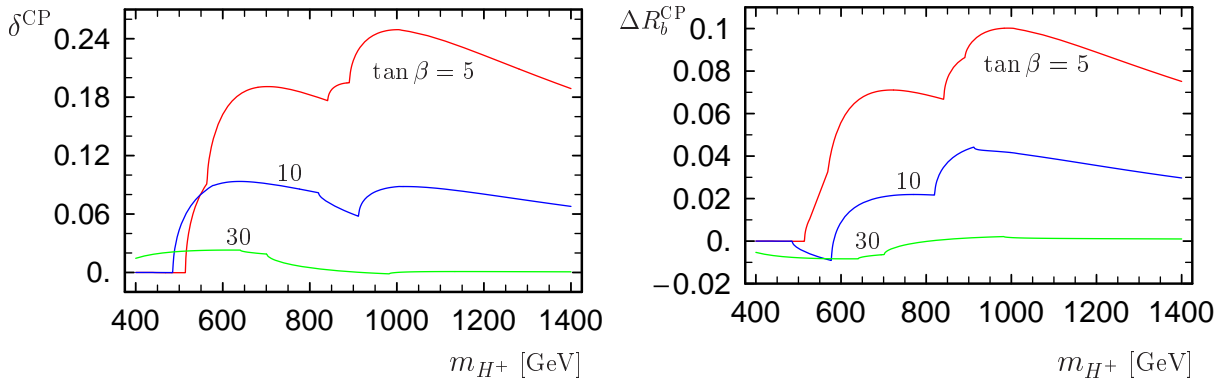


Figure 5: The asymmetries δ^{CP} and ΔR_b^{CP} as functions of m_{H^+} for $\phi_{A_t} = \pi/2$, $\phi_{A_b} = 0$ and a non zero phase of μ , $\phi_\mu = \pi/10$. The red, blue and green lines are for $\tan\beta = 5, 10$, and 30.

where the sum is over the loops with CP-violation shown on Fig. 6. We assume that the squarks are heavy and that the decay $H^+ \rightarrow \tilde{t}\tilde{b}$ is not allowed kinematically. Thus, we are left with the loop corrections with sleptons, charginos and neutralinos. In the commonly discussed models of SUSY breaking, the squarks are much heavier than sleptons, charginos and neutralinos. According to the numerical exploration of the $H^\pm \rightarrow W^\pm h^0$ decay we have the following reasoning.

First, increasing m_{H^+} , the mass m_{h^0} is saturated, approaching its maximum value, $m_{h^0}^{max} \simeq 130$ GeV. There is an experimental lower bound for m_{h^0} , $m_{h^0} \geq 96$ GeV [8]. Thus, respecting both the experimental and theoretical bounds, we consider m_{h^0} in the range $96 \leq m_{h^0} \leq 130$ GeV. Our analysis shows a very weak dependence on m_{h^0} and the results here are presented for $m_{h^0} = 125$ GeV.

The second consequence concerns the $H^\pm W h^0$ coupling which determines the BR ($H^+ \rightarrow W^+ h^0$). It falls down quickly when increasing m_{H^+} and, depending on $\tan\beta$, we can enter the so called decoupling limit, $\cos^2(\beta - \alpha) \rightarrow 0$, where the BR ($H^+ \rightarrow W^+ h^0$) almost vanishes. In order to keep the value of BR ($H^+ \rightarrow W^+ h^0$) at the level of a few percents, we keep m_{H^+} and $\tan\beta$ relatively small: $200 \leq m_{H^+} \leq 600$ GeV and $3 \leq \tan\beta \leq 9$.

In order not to vary too many parameters, we again fix part of the SUSY parameter space:

$$M_2 = 250 \text{ GeV}, M_E = M_L - 5 \text{ GeV}, M_L = 120 \text{ GeV}, |A_\tau| = 500 \text{ GeV}, |\mu| = 150 \text{ GeV}. \quad (27)$$

In order $\delta_{Wh^0}^{CP}$ to be nonzero, we need both new decay channels opened and CP-violating phases present. In accordance with this we have three cases: **1)** When only the decay channels $H^+ \rightarrow \tilde{\nu}\tilde{\tau}_n^+$ are open (Fig. 6a). Then the phase ϕ_τ is responsible for CP violation. **2)** When the decay channels $H^+ \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_k^0$ are open only (Fig. 6b). In this case CP violation is due to the phase ϕ_1 , and **3)** When both $H^+ \rightarrow \tilde{\nu}\tilde{\tau}_n^+$ and $H^+ \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_k^0$ decay channels are kinematically allowed (all diagrams of Fig. 6). In this case the two phases ϕ_τ and ϕ_1 contribute.

Examples of the asymmetry as function of $m_{H^+}^+$ for cases **1)** and **2)** are shown on Fig. 7a

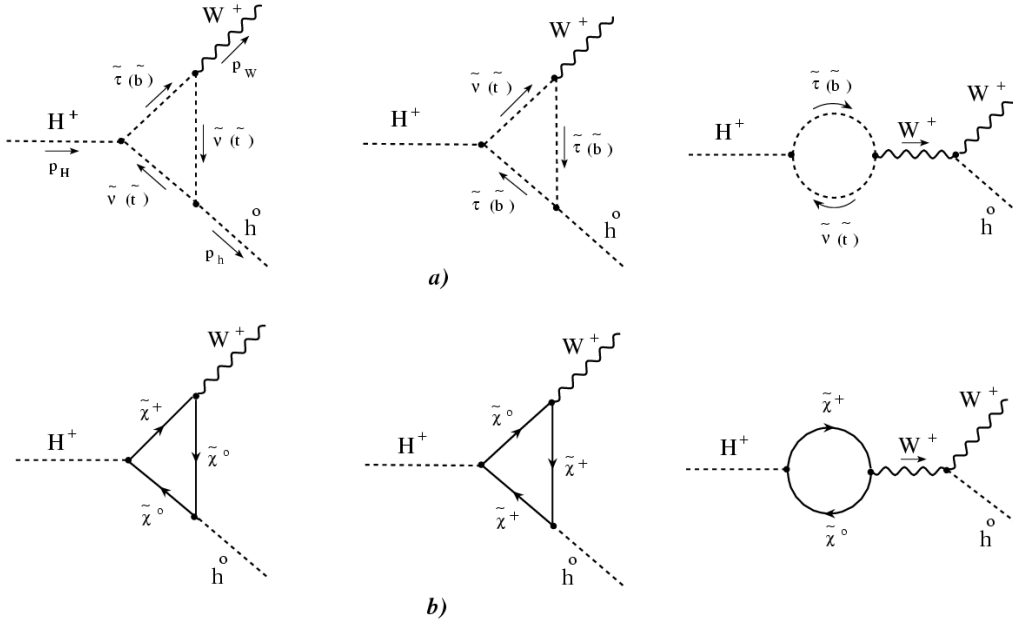


Figure 6: The 1-loop diagrams in MSSM with complex parameters that contribute to $\delta_{Wh^0}^{CP}$

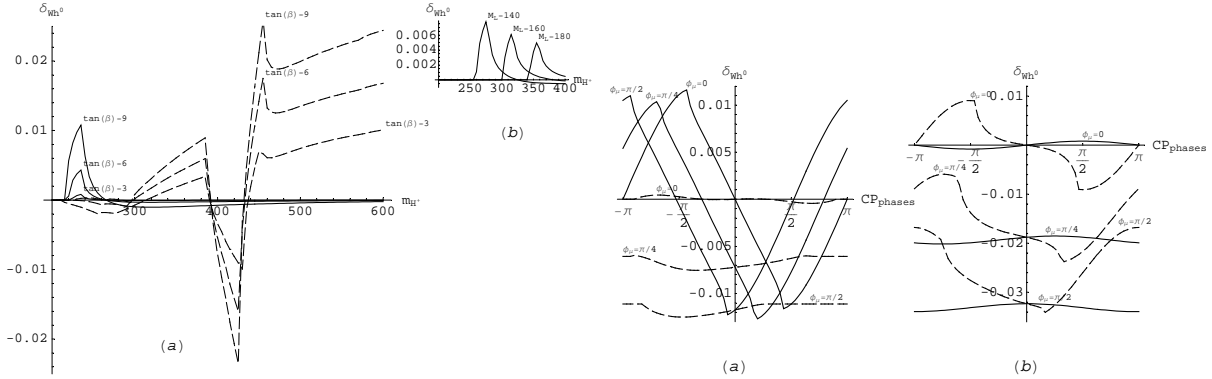


Figure 7: **Left:** δ_{Wh^0} as a function of m_{H^+} **a)** for different values of $\tan\beta$, $M_L = 120$ GeV; solid lines are for $\phi_\tau = -\pi/2$, $\phi_1 = 0$; dashed lines are for $\phi_\tau = 0$, $\phi_1 = -\pi/2$. **b)** for different values of M_L , at $\tan\beta = 9$, $\phi_\tau = -\pi/2$, $\phi_1 = 0$. **Right:** δ_{Wh^0} at $\tan\beta = 9$ versus the CP violating phases ϕ_τ and ϕ_1 for different values of ϕ_μ [$\phi_\mu = 0, \pi/4, \pi/2$]. The solid lines are for $\phi_\tau = [-\pi, \pi]$ while $\phi_1 = 0$; the dashed lines are for $\phi_1 = [-\pi, \pi]$ while $\phi_\tau = 0$, **a)** for $m_{H^+} = 237$ GeV ($= m_{\tilde{\nu}} + m_{\tilde{\tau}_2^+}$) and **b)** for $m_{H^+} = 387$ GeV ($= m_{\tilde{\chi}_2^+} + m_{\tilde{\chi}_1^0}$).

for different values of $\tan\beta$. It is clearly seen that in both cases the asymmetry strongly increases with $\tan\beta$. In both cases, **1)** and **2)**, the asymmetry reaches up to 10^{-2} . The dependence on M_L for case **1)** is seen on Fig. 7b. Case **3)**, when all relevant SUSY particles can be light, is described by the algebraic sum of the two graphs at a given $\tan\beta$

and we don't present it separately. In all these cases the asymmetry does not exceed a few percents.

The effect of a non-zero phase ϕ_μ is seen on Fig. 7. In all cases a CP violating phase of μ does not change the form of the curves but rather shifts the positions of the maxima and, in general, increases the absolute value of the asymmetry.

Let us summarize. We have calculated different asymmetries concerning the quark and boson decay mode of the charged Higgs boson H^\pm , caused by CP-violating phases in the MSSM Lagrangian. The quark decay mode is dominant for large m_{H^+} and the most important phase is the phase of A_t . In this case the decay rate asymmetry can reach up to 25%, and the forward-backward asymmetry can go up to 10%. These asymmetries are rather large and in principle measurable at LHC, but because of the large background of the process, require higher luminosity (e.g. SLHC). The boson decay mode is important for small m_{H^+} and $\tan\beta$ and sensitive to the phases of M_1 and the phase of A_τ . The decay rate asymmetry is, typically, of the order of $10^{-2} \div 10^{-3}$. Concerning its measurability more promising are the next generation linear e^+e^- colliders.

Acknowledgements

This work would not be possible without the valuable contribution of my coauthors Prof. Ekaterina Christova, Prof. Walter Majerotto, Dr. Helmut Eberl and Dr. Mihail Stoilov. I am grateful to all of them.

References

- [1] M. Dugan, B. Grinstein and L. J. Hall, Nucl. Phys. B **255** (1985) 413.
- [2] P. Nath, Phys. Rev. Lett. **66** (1991) 2565; Y. Kizukuri and N. Oshimo, Phys. Rev. D **46** (1992) 3025; Y. Grossman, Y. Nir and R. Rattazzi, Adv. Ser. Direct. High Energy Phys. **15** (1998) 755.
- [3] For a review, see: D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, Phys. Rept. **347** (2001) 1.
- [4] E. Christova, H. Eberl, S. Kraml and W. Majerotto, JHEP **0212** (2002) 021 [hep-ph/0211063].
- [5] E. Christova, E. Ginina, M. Stoilov JHEP **11** (2003) 027 [hep-ph/0307319].
- [6] E. Christova, H. Eberl, E. Ginina and W. Majerotto, JHEP **0702** (2007) 075 [hep-ph/0612088].
- [7] E. Christova, Int. J. Mod. Phys., **A14**(1999)1
- [8] ALEPH, DELPHI,L3,OPAL collaborations, hep-ex/0107029, the group homepage lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html