CP violation in charged Higgs boson decays in the MSSM with complex parameters

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Abstract

Supersymmetric loop contributions can lead to different decay rates of $H^+ \to t\bar{b}$ and $H^- \to b\bar{t}$. We calculate the asymmetry $\delta^{CP} = [\Gamma(H^+ \to t\bar{b}) - \Gamma(H^- \to b\bar{t})] / [\Gamma(H^+ \to t\bar{b}) + \Gamma(H^- \to b\bar{t})]$ at next-to-leading order in the MSSM with complex parameters. We analyse the parameter dependence of δ^{CP} with emphasis on the phases of A_t and A_b. It turns out that the most important contribution comes from the loop with stop, sbottom, and gluino. If this contribution is present, δ^{CP} can go up to 10 – 15%.

Several talks at this conference discussed the issue of CP-violating phases in the supersymmetric (SUSY) Lagrangian. In the Minimal Supersymmetric Standard Model (MSSM), the higgsino parameter μ in the superpotential, two of the soft SUSY-breaking Majorana gaugino masses M_i ($i = 1, 2, 3$), 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]. From the point of view of baryogenesis, one might hope that these phases are large [2]. On the other hand, the experimental limits on electron and neutron electric dipole moments (EDMs) [3], $|d^e| \leq 2.15 \times 10^{-13}$ e/GeV, $|d^n| \leq 5.5 \times 10^{-12}$ e/GeV, place severe constraints on the phase of μ, $\phi_\mu < \mathcal{O}(10^{-2})$ [4], for a typical SUSY mass scale of the order of a few hundred GeV. A larger ϕ_μ imposes fine-tuned relationships between this phase and other SUSY parameters [5]. Phases of the trilinear couplings of the third generation $A_{t,b,\tau}$ are much less constrained and can lead to significant CP-violation effects, especially in top quark physics [6]. Moreover, they can have a significant influence on the phenomenology of stop, sbottoms, and staus [7]. Phases of μ and $A_{t,b,\tau}$ also affect the Higgs sector in a relevant way. Although the Higgs potential of the MSSM is invariant under CP at tree level, at loop level CP is sizeably violated by complex couplings [8, 9, 10]. As a consequence, the three neutral mass eigenstates H_l^0 ($l = 1, 2, 3$) are superpositions of the CP eigenstates h^0, H^0, and A^0.

In this contribution, we discuss CP violation in the decays of charged Higgs bosons within the MSSM with complex parameters. In particular, we concentrate on the decays into top and bottom quarks. Here SUSY loop contributions can lead to a CP-violating asymmetry

$$\delta^{CP} = \frac{\Gamma(H^+ \to t\bar{b}) - \Gamma(H^- \to b\bar{t})}{\Gamma(H^+ \to t\bar{b}) + \Gamma(H^- \to b\bar{t})} \tag{1}$$

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which could be measured in a counting experiment. We calculate δ^{CP} at the one-loop level in the MSSM with phases and discuss its parameter dependence. Analogous asymmetries can of course be obtained for other decay channels of $H^\pm$, such as $H^\pm \to \tau\nu$, $H^\pm \to \tilde{\chi}^\pm\tilde{\chi}^0$, $H^\pm \to \tilde{t}\tilde{b}$.

We first discuss the basic formulae for the $H^\pm \to tb$ decays. The decay widths at tree level are given by

$$\Gamma^0\,(H^\pm \to tb) = \frac{3\kappa}{16\pi m_{H^+}^3}\left[(m_{H^+}^2 - m_t^2 - m_b^2)(y_t^2 + y_b^2) - 4m_t m_b y_t y_b\right], \tag{2}$$

where $\kappa = \kappa(m_{H^+}^2, m_t^2, m_b^2)$, $\kappa(x,y,z) = [(x-y-z)^2 - 4yz]^{1/2}$ and

$$y_t = h_t \cos\beta\,, \qquad y_b = h_b \sin\beta\,, \tag{3}$$

with h_t and h_b the top and bottom Yukawa couplings. Since there is no CP violation at tree level, $\Gamma^0(H^+ \to t\bar{b}) = \Gamma^0(H^- \to b\bar{t})$. At one loop, however, we have

$$y_i \to Y_i^\pm = y_i + \delta Y_i^\pm \quad (i = t, b)\,, \tag{4}$$

and thus

$$\begin{aligned}\Gamma\,(H^\pm \to tb) = \frac{3\kappa}{16\pi m_{H^+}^3}\big[&(m_{H^+}^2 - m_t^2 - m_b^2)(y_t^2 + y_b^2 + 2y_t\,\mathrm{Re}\,\delta Y_t^\pm + 2y_b\,\mathrm{Re}\,\delta Y_b^\pm)\\ &- 4m_t m_b(y_t y_b + y_t\,\mathrm{Re}\,\delta Y_b^\pm + y_b\,\mathrm{Re}\,\delta Y_t^\pm)\big]\,,\end{aligned} \tag{5}$$

where δY_i^+ $(i = t, b)$ stands for the decay of H^+ and δY_i^- for the decay of H^-. These form factors have, in general, both CP-invariant and CP-violating contributions:

$$\delta Y_i^\pm = \delta Y_i^{inv} \pm \tfrac{1}{2}\,\delta Y_i^{CP}\,. \tag{6}$$

Both the CP-invariant and the CP-violating contributions have real and imaginary parts. CP invariance implies $\mathrm{Re}\,\delta Y_i^+ = \mathrm{Re}\,\delta Y_i^-$. Using eqs. (5) and (6), we can write the CP-violating asymmetry δ^{CP} of eq. (1) as

$$\delta^{CP} = \frac{\Delta\,(y_t\,\mathrm{Re}\,\delta Y_t^{CP} + y_b\,\mathrm{Re}\,\delta Y_b^{CP}) - 2m_t m_b(y_t\,\mathrm{Re}\,\delta Y_b^{CP} + y_b\,\mathrm{Re}\,\delta Y_t^{CP})}{\Delta\,(y_t^2 + y_b^2) - 4m_t m_b\, y_t y_b}\,, \tag{7}$$

where $\Delta = m_{H^+}^2 - m_t^2 - m_b^2$. δ^{CP} gets contributions from loop exchanges of $\tilde{t}$, $\tilde{b}$, $\tilde{g}$, $\tilde{\chi}^\pm$, $\tilde{\chi}^0$, W, and neutral Higgs bosons. In principle, there would also be a contribution due to $\tilde{\nu}$ and $\tilde{\tau}$ exchange, which can, however, be neglected in our study. The relevant Feynman diagrams are shown in Fig. 1. The explicit expressions for $\delta Y_{t,b}^{CP}$ due to these diagrams are given in [11]. Of course, the various diagrams contribute to δ^{CP} only if they have absorptive parts. Here note that the diagram with WH^0b always contributes, since $m_t > m_W + m_b$. The dominant contribution, however, comes from the $\tilde{t}\tilde{b}\tilde{g}$ loop, provided the channel $H^\pm \to \tilde{t}\tilde{b}$ is open.

Let us now turn to the numerical analysis. In order not to vary too many parameters, we fix part of the parameter space at the electroweak scale by the choice

$$\begin{aligned}&M_2 = 200\text{ GeV},\ \mu = -350\text{ GeV},\ M_{\tilde{Q}} = 350\text{ GeV},\\ &M_{\tilde{Q}} : M_{\tilde{U}} : M_{\tilde{D}} = 1 : 0.85 : 1.05,\ A_t = A_b = -500\text{ GeV}.\end{aligned} \tag{8}$$

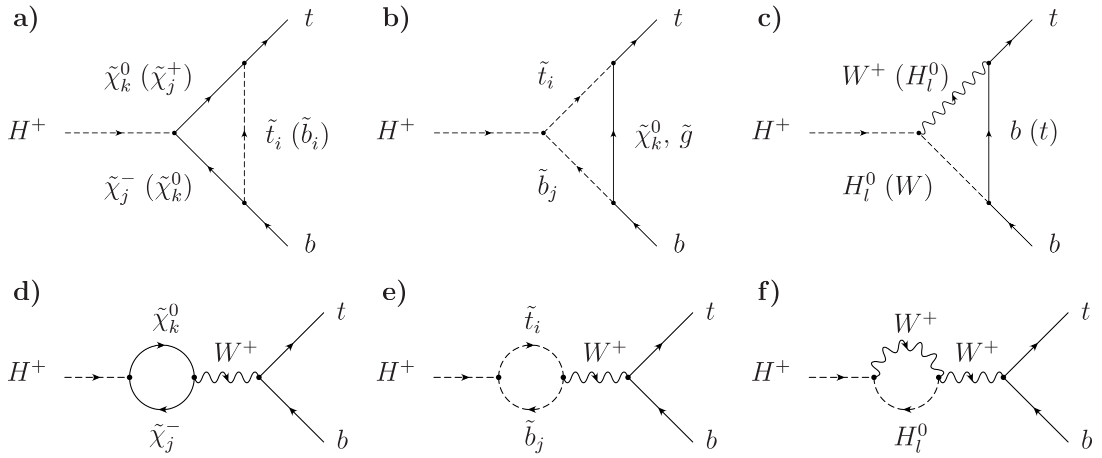

Figure 1: Sources for CP violation in $H^+ \to t\bar{b}$ decays at 1-loop level in the MSSM with complex couplings ($i, j = 1, 2$; $k = 1, ..., 4$; $l = 1, 2, 3$).

Moreover, we assume GUT relations for the gaugino mass parameters M_1, M_2, M_3. In this case, the phases of the gaugino sector can be rotated away. Since ϕ_μ, the phase of μ, is highly constrained by the EDMs of electron and neutron, we take $\phi_\mu = 0$. The phases relevant to our study are thus ϕ_t and ϕ_b, the phases of A_t and A_b. For the choice eq. (8), $\tan\beta = 10$ and $\phi_t = 0$ ($\pi/2$), we get $m_{\tilde{t}_1} = 226$ (213) GeV, $m_{\tilde{t}_2} = 465$ (471) GeV, $m_{\tilde{b}_1} = 340$ GeV, and $m_{\tilde{b}_2} = 382$ GeV.

Figure 2a shows δ^{CP} as a function of m_{H^+} for $\tan\beta = 10$. For $m_{H^+} < m_{\tilde{t}_1} + m_{\tilde{b}_1}$, δ^{CP} is very small, $\mathcal{O}(10^{-3})$ or smaller. The contributions come from the diagrams of Figs. 1a, 1c, and 1f; the diagram of Fig. 1d only contributes if there is a non-zero phase in the chargino/neutralino sector. However, once the $H^+ \to \tilde{t}\bar{\tilde{b}}$ channel is open, δ^{CP} can go up to several per cent. The thresholds of $H^+ \to \tilde{t}_1\bar{\tilde{b}}_1$ at $m_{H^+} \simeq 550$ GeV, and of $H^+ \to \tilde{t}_2\bar{\tilde{b}}_1$ at $m_{H^+} \simeq 810$ GeV are clearly visible in Fig. 2a. For $m_{H^+} = 700$ GeV, we obtain $\delta^{CP} \sim -5\%$, -9%, and -12% for $\phi_t = \pi/8$, $\pi/4$, and $\pi/2$, respectively. For $m_{H^+} = 900-1000$ GeV, δ^{CP} goes up to almost 17%. The dominant contribution comes from the stop–sbottom–gluino loop of Fig. 1b. Also the stop–sbottom–neutralino loop of Fig. 1b and the stop–sbottom self-energy of Fig. 1e can give a relevant contribution and should thus be taken into account. The contribution of the graphs with $\tilde{\chi}^\pm\tilde{\chi}^0$ or H^0W (Fig. 1a,c,f) exchange can, however, be neglected in this case. Here a remark is in order: To calculate the latter contributions with neutral Higgs bosons, we have used [9, 12]. This is sufficient for our purpose, since we are mainly interested in large CP-violating effects that occur for $m_{H^+} > m_{\tilde{t}_1} + m_{\tilde{b}_1}$ because of $\phi_{t,b}$. However, once precision measurements of $H^\pm$ decays become feasible, a more complete calculation of the H_l^0 masses and couplings [10] might be used.

Figure 2b shows the $\tan\beta$ dependence of δ^{CP} for $m_{H^+} = 700$ GeV and the cases $\phi_t = \pi/2$, $\phi_b = 0$ (full line) and $\phi_t = \phi_b = \pi/2$ (dashed line). It turns out that the asymmetry has a maximum around $\tan\beta \simeq 10$ and decreases for larger $\tan\beta$. For $\phi_t = \pi/2$ and $\phi_b = 0$, we have $\delta^{CP} \sim -12\%$ at $\tan\beta = 10$ and $\delta^{CP} \sim -3.5\%$ at $\tan\beta = 40$. An additional phase of A_b can enhance or reduce the asymmetry. For the parameters eq. (8),

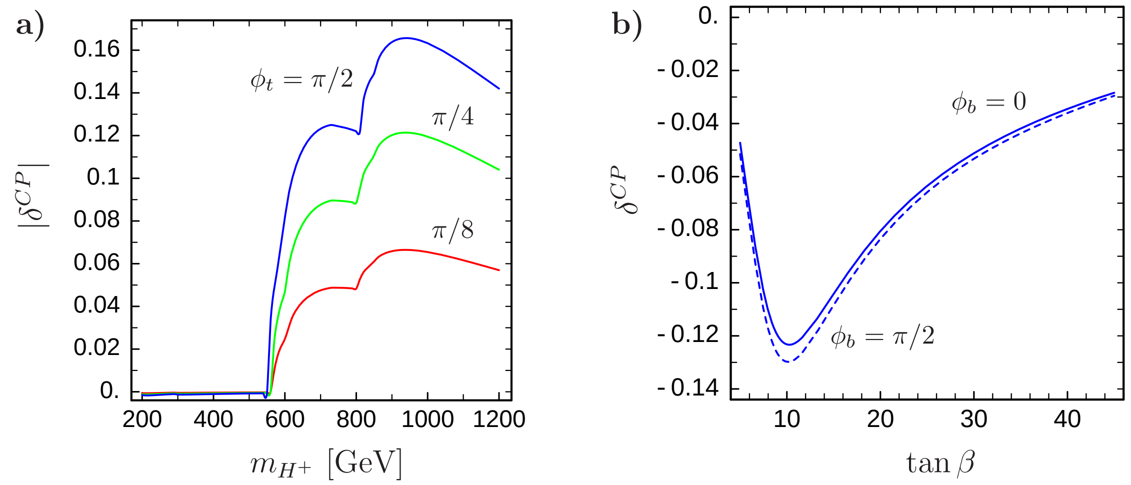

Figure 2: The decay rate asymmetry δ^{CP} of $H^{\pm} \to tb$ in **(a)** as a function of m_{H^+} for $\tan\beta = 10$ and $\phi_b = 0$, in **(b)** as a function of $\tan\beta$, for $m_{H^+} = 700$ GeV and $\phi_t = \pi/2$. The other parameters are fixed by eq. (8).

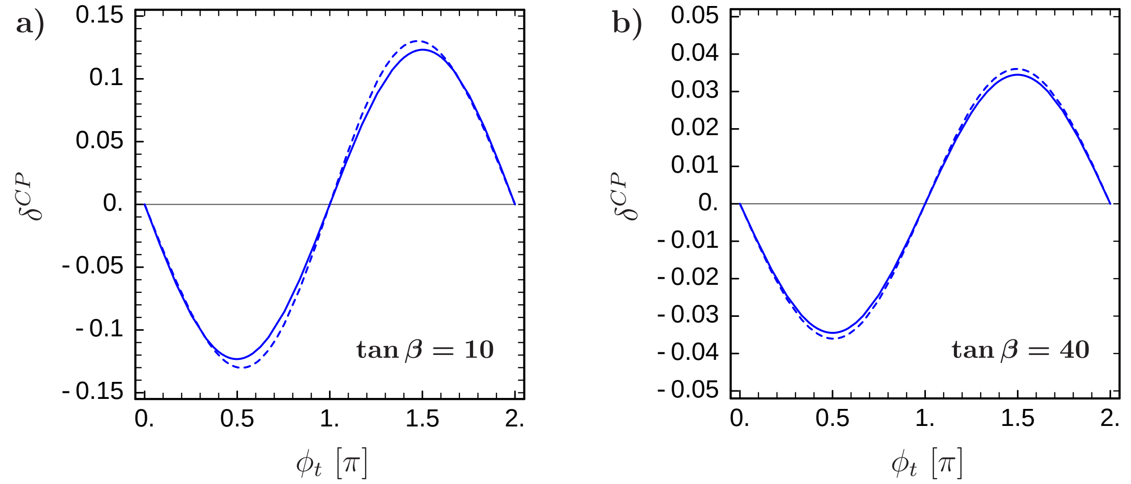

Figure 3: δ^{CP} as a function of ϕ_t, for $m_{H^+} = 700$ GeV, $\tan\beta = 10$ in **(a)** and $\tan\beta = 40$ in **(b)**; full lines: $\phi_b = 0$, dashed lines: $\phi_b = \phi_t$. The other parameters are fixed by eq. (8).

however, it turns out that the effects in the triangle and self-energy graphs of Fig. 1b and 1e compensate each other so that the overall dependence on ϕ_b is small.

The dependence on ϕ_t is shown explicitly in Fig. 3, where we plot δ^{CP} as a function of ϕ_t, for $m_{H^+} = 700$ GeV and $\tan\beta = 10$ and 40. As expected, δ^{CP} shows a $\sin\phi_t$ dependence. Here note that the branching ratio of $H^+ \to t\bar{b}$ increases with $\tan\beta$. For $m_{H^+} = 700$, in the case of vanishing phases, we have $\mathrm{BR}(H^+ \to t\bar{b}) \simeq 17\%$ (85%) for $\tan\beta = 10$ (40).

Last but not least we relax the GUT relations between the gaugino masses and take $m_{\tilde{g}}$ as a free parameter (keeping, however, the relation between M_1 and M_2 and taking

$M_3 = m_{\tilde{g}}$ real). Figure 4 shows the dependence of δ^{CP} on the gluino mass for $m_{H^+} =$ 700 GeV, $\phi_t = \pi/2$, $\phi_b = 0$, and $\tan\beta = 10$ and 40. As one can see, the gluino does not decouple. Even for a large gluino mass, an asymmetry of a few per cent is possible. A non-zero phase of M_3 may also have a large effect. It can, in fact, lead to an asymmetry of $\mathcal{O}(10\%)$ even if all other phases are zero [11].

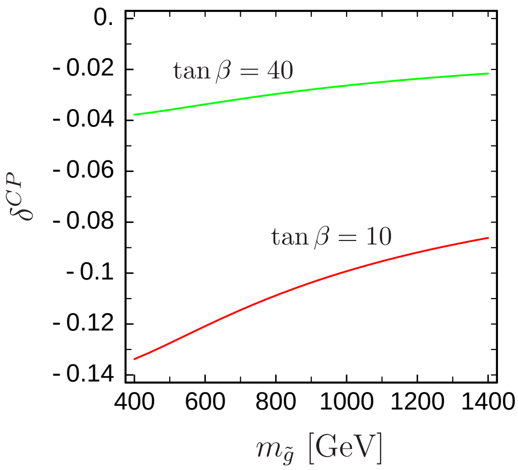

Figure 4: δ^{CP} as a function of $m_{\tilde{g}}$, for $m_{H^+} = 700$ GeV, $\phi_t = \pi/2$, $\phi_b = 0$, $\tan\beta = 10$ and 40. The other parameters are fixed by eq. (8).

Some remarks on the measurability are in order. At the Tevatron, no sensitivity for detecting $H^\pm$ is expected for a mass $m_{H^+} \gtrsim 200$ GeV. The LHC, on the other hand, has a discovery reach up to $m_{H^+} \sim 1$ TeV, especially if QCD and SUSY effects conspire to enhance the cross section. With a luminosity of $\mathcal{L} = 100$ fb^{-1}, about 217 signal events can be expected for $pp \to H^+\bar{t}b$ with $S/\sqrt{B} = 6.3$, for $m_{H^+} \simeq 700$ GeV and $\tan\beta = 50$ [13]. However, the region $\tan\beta \lesssim 20$ seems to be very difficult. In e^+e^- collisions, the dominant production mode is $e^+e^- \to H^+H^-$. For the mass ranges relevant to our study this would require a TeV-scale linear collider. Indeed, for $m_{H^+} \sim 700$ GeV, BR$(H^\pm \to tb)$ could be measured to few per cent at CLIC [14].

To summarize, we have calculated the difference between the partial decay rates $\Gamma\,(H^+ \to t\bar{b})$ and $\Gamma\,(H^- \to \bar{t}b)$ due to CP-violating phases in the MSSM. The resulting rate asymmetry δ^{CP}, eq. (1), could be measured in a counting experiment. If $m_{H^+} < m_{\tilde{t}_1} + m_{\tilde{b}_1}$, δ^{CP} is typically of the order of 10^{-3}. However, for $m_{H^+} > m_{\tilde{t}_1} + m_{\tilde{b}_1}$, δ^{CP} can go up to $10-15\%$, depending on the phases of A_t, A_b, and μ, and on $\tan\beta$. Such a large asymmetry should be measurable at future colliders such as LHC or CLIC.

References

[1] M. Dugan, B. Grinstein, and L. J. Hall, Nucl. Phys. B **255** (1985) 413.

[2] M. Carena, M. Quiros, and C. E. Wagner, Nucl. Phys. B **524** (1998) 3; for a review see: A. G. Cohen, D. B. Kaplan and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **43** (1993) 27.

[3] I. S. Altarev *et al.*, Phys. Lett. B **276** (1992) 242; I. S. Altarev *et al.*, Phys. Atom. Nucl. **59** (1996) 1152 [Yad. Fiz. **59N7** (1996) 1204]; E. D. Commins, S. B. Ross, D. DeMille and B. C. Regan, Phys. Rev. A **50** (1994) 2960.

[4] P. Nath, Phys. Rev. Lett. **66** (1991) 2565; Y. Kizukuri and N. Oshimo, Phys. Rev. D **46** (1992) 3025; R. Garisto and J. D. Wells, Phys. Rev. D **55** (1997) 1611; Y. Grossman, Y. Nir, and R. Rattazzi, Adv. Ser. Direct. High Energy Phys. **15** (1998) 755.

[5] T. Ibrahim and P. Nath, Phys. Lett. B **418** (1998) 98; M. Brhlik, G. J. Good ,and G. L. Kane, Phys. Rev. D **59** (1999) 115004; A. Bartl, T. Gajdosik, W. Porod, P. Stockinger, and H. Stremnitzer, Phys. Rev. D **60** (1999) 073003.

[6] For a review, see: D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, Phys. Rept. **347** (2001) 1.

[7] A. Bartl, T. Kernreiter, and W. Porod, hep-ph/0202198; A. Bartl, K. Hidaka, T. Kernreiter, and W. Porod, hep-ph/0204071.

[8] A. Pilaftsis, Phys. Rev. D **58** (1998) 096010 and Phys. Lett. B **435** (1998) 88; A. Pilaftsis and C. E. Wagner, Nucl. Phys. B **553** (1999) 3; D. A. Demir, Phys. Rev. D **60** (1999) 055006.

[9] M. Carena, J. R. Ellis, A. Pilaftsis, and C. E. Wagner, Nucl. Phys. B **586** (2000) 92.

[10] M. Carena, J. R. Ellis, A. Pilaftsis, and C. E. Wagner, Nucl. Phys. B **625** (2002) 345; S. Heinemeyer, Eur. Phys. J. C **22** (2001) 521; T. Ibrahim and P. Nath, hep-ph/0204092.

[11] E. Christova, H. Eberl, W. Majerotto, and S. Kraml, Nucl. Phys. B **639** (2002) 263, erratum ibidem (to appear), hep-ph/0205227.

[12] Fortran program `cph.f`, `http://pilaftsi.home.cern.ch/pilaftsi/`

[13] A. Belyaev, D. Garcia, J. Guasch, and J. Sola, hep-ph/0203031.

[14] M. Battaglia, A. Ferrari, A. Kiiskinen, and T. Maki, hep-ex/0112015, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. R. Davidson and C. Quigg; A. Ferrari, private communication.