Self-couplings of Higgs bosons in the CP-violating scenarios

E.N. Akhmetzyanova, M.V. Dolgopolov, M.N. Dubinin

Dept. of General and Theoretical Physics, Samara State University,
443011 Samara, Akad. Pavlov str. 1., Russia;
D.V. Skobeltsyn Institute of Nuclear Physics, Moscow State University,
119992 Moscow, Vorobyevi Gory, Russia.

Abstract

The trilinear and the quartic couplings of physical Higgs bosons in the MSSM with explicit CP violation in the two-doublet Higgs sector are calculated within the framework of the CPX scenario. The magnitude of an effective coupling changes several times with the variation of the CP violating phase $\mathtt{arg}(\mu A)$, being very sensitive to the radiative corrections taken at the one-loop/two-loop level. At the phase values around $\pi/2$ zeroes of selfcouplings take place.

1 Introduction

General two-Higgs-doublet potential with real parameters λ_1-λ_4 and complex-valued parameters λ_5, λ_6, λ_7 is not a CP invariant object, thus providing an interesting possibility to introduce to a theory a source of CP violation different from the standard CKM mixing matrix. This possibility has been extensively analysed in the framework of the minimal supersymmetric model (MSSM) [1]. The effective two-doublet Higgs potential of the MSSM at the energy scale m_{top} has the form of a general two-Higgs-doublet potential, where the parameters λ_1-λ_7 can be calculated explicitly [2, 3, 4] and expressed through the parameters of the MSSM in the sector of scalar quarks–Higgs bosons interaction. In this sense the MSSM Higgs sector as an effective field theory at the scale m_{top} can be embedded in a general two-Higgs-doublet model (THDM) [5], providing a possibility to interpret general THDM features in the language of the MSSM parameter space.

In the following we are using the formalism described in [3, 5] for the evaluation of observables with the explicit CP violation in the MSSM two-doublet Higgs sector. First the mass eigenstates of CP conserving limit $\mathtt{Im}\lambda_{5,6,7}=0$ which are h, H (CP-even scalars), A (CP-odd scalar) and $H^{\pm}$ (charged scalar) are defined in a standard way (using the two mixing angles α and β). If the nonzero imaginary parts of $\lambda_{5,6,7}$ are generated in the effective potential by the scalar fields interaction with the third generation sfermions, the mass eigenstates of the CP conserving limit (h, H, A) are rotated by the $3{\times}3$ mixing matrix a_{ij} to define the physical Higgs fields (h_1, h_2, h_3) [5]. In comparison with other approaches [6, 7] we introduce the α-rotation of the h and H states respecting the CP conserving scenario, if the parameters are taken real-valued (e.g. for real parameters h and H are the mass eigenstates of the CP conserving case). In this sense the CP conserving limit is explicitly constructed. Nevertheless the mass splitting of physical states (h_1, h_2, h_3) without a definite CP parity does not depend on the diagonalization procedure [3].

The evaluation of λ_{1-7} parameters [3] is based on the effective field theory approach [4]. The two-Higgs-doublet effective potential parameters are calculated using the MSSM potential of the Higgs bosons-scalar quarks interaction and include the contributions coming from the F-terms, leading and nonleading D-terms, the wave-function renormalization terms, and leading two-loop Yukawa QCD-corrections.

In this proceeding we calculate the trilinear and the quartic couplings of physical Higgs bosons in the CPX scenario [11] of the MSSM. Continious interest to the self-interactions of Higgs bosons both in the case of CP conservation [8] and the case of CP violation [6, 9] is motivated by the experimental accessibility of the two and three Higgs bosons production signals [10] providing possibilities to reconstruct experimentally the effective Higgs potential.

2 Self-interaction of physical Higgs bosons

The effective trilinear and quartic couplings of physical Higgs bosons h_1, h_2 and h_3 (i.e. their mass term $m_{ij}h_ih_j$ in the two-doublet potential is diagonal $m_{ij} = m_{h_i}\,\delta_{ij}$ in the local minimum) can be written in a compact form:

$$\mathcal{L}_{3H} = v \sum_{i\ge j\ge k=1}^{3} g_{h_i h_j h_k} \frac{1}{N_S^{ijk}} h_i h_j h_k + v \sum_{i=1}^{3} g_{h_i H^+ H^-} h_i H^+ H^- , \tag{1}$$

$$\mathcal{L}_{4H} = \sum_{i\ge j\ge k\ge l=1}^{3} g_{h_i h_j h_k h_l} \frac{1}{N_S^{ijkl}} h_i h_j h_k h_l + \sum_{i\ge j=1}^{3} g_{h_i h_j H^+ H^-} \frac{1}{N_S^{ij}} h_i h_j H^+ H^- \tag{2}$$

$$+ \frac{1}{4} g_{H^+ H^- H^+ H^-} (H^+ H^-)^2 , \tag{3}$$

where N_S are the combinatorial factors and

$$g_{h_i h_j h_k} = \sum_{\alpha\le\beta\le\gamma=1}^{3} \{a_{\alpha i} a_{\beta j} a_{\gamma k}\}\, g_{\alpha\beta\gamma} , \qquad g_{h_i H^+ H^-} = \sum_{\alpha=1}^{3} a_{\alpha i}\, g_{\alpha H^+ H^-} , \tag{4}$$

$$g_{h_i h_j h_k h_l} = \sum_{\alpha\le\beta\le\gamma\le\delta=1}^{3} \{a_{\alpha i} a_{\beta j} a_{\gamma k} a_{\delta l}\}\, g_{\alpha\beta\gamma\delta} , \qquad g_{h_i h_j H^+ H^-} = \sum_{\alpha\le\beta=1}^{3} \{a_{\alpha i} a_{\beta j}\}\, g_{\alpha\beta H^+ H^-} . \tag{5}$$

Couplings $g_{\alpha\beta\gamma}$, $g_{\alpha H^+H^-}$, $g_{\alpha\beta\gamma\delta}$ and $g_{\alpha\beta H^+H^-}$ are the intermediate expressions defined in the unphysical basis. Expressions in curly brackets in (4)–(5) should be symmetrised in the indexes i, j, k, l, and also the corresponding combinatorial factors, when two or more indexes coincide, should be taken into account. For example, $\{a_{\alpha i} a_{\beta j} a_{\gamma k}\}$ has the representation

$$\{a_{\alpha i} a_{\beta j} a_{\gamma k}\} \equiv \frac{1}{N_S} \Big(a_{\alpha i} a_{\beta j} a_{\gamma k} + a_{\alpha i} a_{\beta k} a_{\gamma j} + a_{\alpha j} a_{\beta i} a_{\gamma k} + a_{\alpha j} a_{\beta k} a_{\gamma i} + a_{\alpha k} a_{\beta i} a_{\gamma j} + a_{\alpha k} a_{\beta j} a_{\gamma i} \Big) \tag{6}$$

where $N_S = 6$ at $i = j = k$, $N_S = 1$ at $(i, j, k) = (3, 2, 1)$, and $N_S = 2$ in all other cases.

3 Restrictions on the parameter space from the squark sector

It is well-known that the restrictions on the MSSM parameter space appear from the requirement of scalar quark masses to be positively defined. In the framework of the CPX scenario [11] when the MSSM parameters M_{SUSY}, μ and $A_{t,b}$ are large enough and respect the constraints $|\mu| = 2M_{SUSY}$, $|A_t| = |A_b| = 4M_{SUSY}$, the stop and sbottom quark masses were calculated, see Fig. 1, as a two-dimensional function of the CP violating phase $\varphi = \mathtt{arg}(\mu A_{t,b})$ and the supersymmetry scale M_{SUSY}. The stop mass $\tilde{t}_1$ is positively defined in large enough regions of the parameter space (φ, M_{SUSY}) at large $\mathtt{tg}\beta$ (left plot in Fig. 1, while the physical sbottom quark favours small values of $\mathtt{tg}\beta$ (see the right plot). Two plots in Fig. 2 demonstrate the excluded regions of M_{SUSY}, for large $\mathtt{tg}\beta$ a low supersymmetry scale $M_{SUSY} < 500$ GeV is not accepted (right plot) while for a small $\mathtt{tg}\beta$ the region of moderate M_{SUSY} is excluded at large values of the phase φ. For the scenario with $M_{SUSY} \approx 300$ GeV positively defined squark masses are possible only in a strongly restricted regions of the (μ, A) parameter space, see Fig. 3 where we calculate the scalar quark masses at $\varphi = \pi$.

4 Higgs boson self-couplings in the CPX scenario

The effective trilinear and quartic Higgs boson self-couplings can be written down in the two representations. First one uses λ_i parameters and second representation expresses the effective couplings by means of scalar masses in the CP conserving limit φ =0. For example, the effective charged Higgs triple coupling in the lambda-basis can be written as

$$\begin{aligned} g_{1H^+H^-} = {} & \mathtt{Re}\Delta\lambda_5\, s_\beta c_\beta\, c_{\alpha+\beta} - \mathtt{Re}\Delta\lambda_6\, c_\alpha\, s_\beta^2\, c_\beta + \mathtt{Re}\Delta\lambda_6\, s_\alpha\, s_\beta^3 - \mathtt{Re}\Delta\lambda_6\, s_\alpha\, s_{2\beta}\, c_\beta \\ & + \mathtt{Re}\Delta\lambda_7\, c_\beta \left(s_\alpha\, s_\beta\, c_\beta - c_\alpha \left(c_\beta^2 - 2\, s_\beta^2 \right) \right) \\ & - 2\, s_\alpha\, s_\beta^2\, c_\beta\, \lambda_1 + 2\, c_\alpha\, s_\beta\, c_\beta^2\, \lambda_2 - c_\beta^3\, s_\alpha\, \lambda_3 + c_\alpha\, s_\beta^3\, \lambda_3 - c_\beta\, s_\beta\, \lambda_4\, c_{\alpha-\beta} \end{aligned}$$

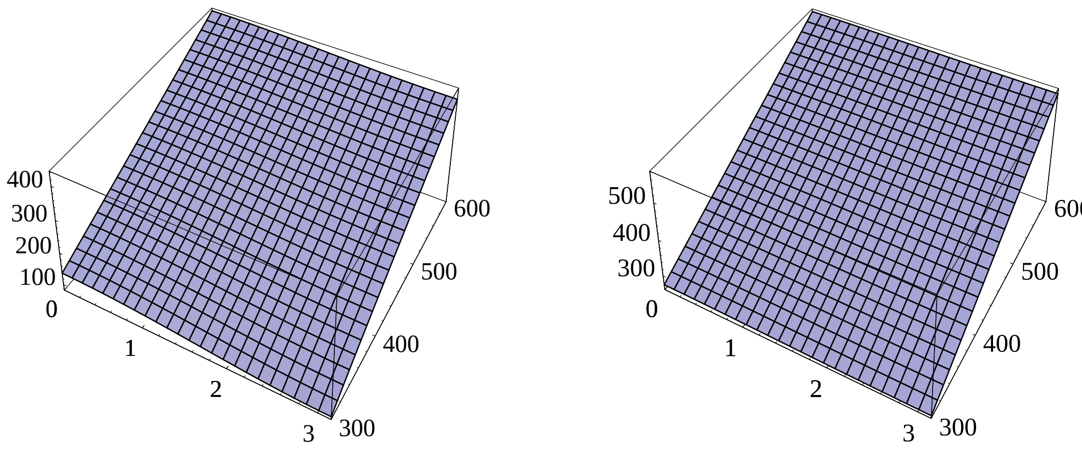


Figure 1: Stop mass m_{t_1} (the left figure for $\texttt{tg}\beta = 40$) and sbottom mass m_{b_1} (the right figure for $\texttt{tg}\beta = 5$) in the CPX scenario, $|\mu| = 2M_{SUSY}$, $|A_t| = |A_b| = 4M_{SUSY}$ vs the phase $\varphi = \texttt{arg}(\mu A_t) = \texttt{arg}(\mu A_b)$, changing from 0 to π, and M_{SUSY}, changing from 300 GeV to 600 GeV.

$$
\begin{aligned}
g_{_{2H^+H^-}} \quad &= \quad \texttt{Re}\Delta\lambda_5\, s_\beta c_\beta\, s_{\alpha+\beta} + 2\,\texttt{Re}\Delta\lambda_6\, c_\alpha\, s_\beta\, c_\beta^2 - \texttt{Re}\Delta\lambda_6\, c_\alpha\, s_\beta^3 - \texttt{Re}\Delta\lambda_6\, s_\alpha\, s_\beta^2 c_\beta \\
&\quad - \texttt{Re}\Delta\lambda_7\, c_\beta\, \left(c_\alpha\, s_\beta\, c_\beta \,+\, s_\alpha\, \left(c_\beta^2 - 2\, s_\beta^2\right)\right) \\
&\quad +2\; c_\alpha\, s_\beta^2\, c_\beta \lambda_1 \,+2\; s_\alpha\, s_\beta\, c_\beta^2 \lambda_2 \,+\, c_\alpha\, c_\beta^3 \lambda_3 \,+\, s_\alpha\, s_\beta^3 \lambda_3 \,-\, c_\beta\, s_\beta\, \lambda_4\, s_{\alpha+\beta} \\
g_{_{3H^+H^-}} \quad &= \quad c_\beta^2\, \texttt{Im}\Delta\lambda_7 \,-\, s_\beta\, c_\beta\, \texttt{Im}\Delta\lambda_5 \,+\, s_\beta^2\, \texttt{Im}\Delta\lambda_6
\end{aligned}
$$

The representation in the mass basis can be found in [3]. The magnitude of the coupling $g_{H^+\,H^-\,h_1}$ is shown in Fig. 4.

Two representations of the effective one- or two-loop Higgs boson self-couplings are equivalent and use either effective λ_i parameters or radiatively corrected masses of the CP conserving limit, calculated at the one- or two- loop level of precision. The mass representation seems to be more convenient for the analysis of limiting cases (e.g. the 'decoupling limit', when the h is light and has standard-like couplings to fermions, and H,A,$H^\pm$ are heavy and nearly degenerate in mass). Note that at $\varphi \sim \pi/2$ the coupling $g_{H^+H^-h_1}$ is zero, and may be negative and positive at different values of the phase around $\sim \pi/2$. The Θ parameter participating in Cardano formula for Higgs mass eigenvalue (see e.g. [3]) has a maximum at this point of zero self-interaction, when $m_{h_1} = m_{h_2}$ in the intense coupling regime. Some numerical values of the physical couplings in the CPX scenario are listed in Table 1–3 and displayed in Fig. 5. In the column denoted by 'SUSY' we give the values of the couplings at the scale M_{SUSY} which is the boundary condition for the effective field theory of the Higgs sector at the scale m_{top} under consideration.

The decay width $h_3 \to h_1 h_2$ has the form

$$
\Gamma_{h_3 \to h_1 h_2} = \sqrt{(m_{h_3}^2 - m_{h_1}^2 - m_{h_2}^2)^2 - 4 m_{h_1}^2 m_{h_2}^2}\; \frac{(v\, g_{h_3 h_1 h_2})^2}{16\,\pi\, m_{h_3}^3} \tag{7}
$$

The decay width $h_j \to h_i h_i$, $j > i$, can be written as

$$
\Gamma_{h_j \to h_i h_i} = \sqrt{1 - (4\, m_{h_i}^2 / m_{h_j}^2)}\; \frac{(v\, g_{h_i h_i h_j})^2}{32\,\pi\, m_{h_j}} \tag{8}
$$

see Fig. 6. At the charged Higgs boson mass $m_{H^\pm} \sim 200$ GeV the decay at the one-loop and at the two-loop is not possible kinematically since $m_{h_2} < 2 m_{h_1}$. Decay widths of the two heavier neutral Higgs bosons h_2, h_3 are very sensitive to the phase φ. Qualitatively, CP violation shows up in the mixing between the CP–odd Higgs state and, mainly, the heavy CP–even Higgs state with decay patterns of the

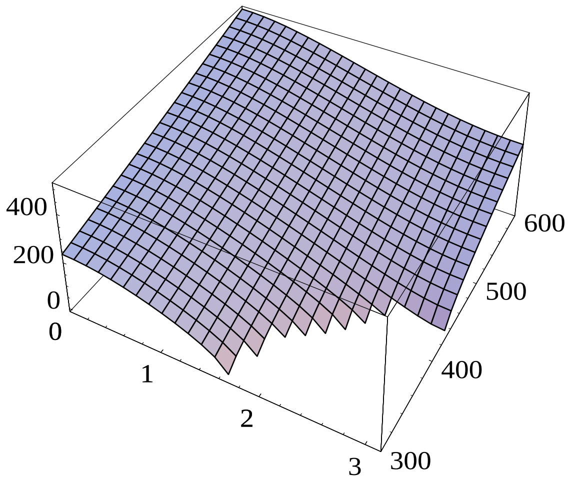


Figure 2: Stop mass m_{t_1} (the left figure for $\mathtt{tg}\beta$ =5) and sbottom mass m_{b_1} (the right figure for $\mathtt{tg}\beta$ =40) in the CPX scenario [11], $|\mu| = 2M_{SUSY}$, $|A_t| = |A_b| = 4M_{SUSY}$, vs the phase $\varphi = \mathtt{arg}(\mu A_t) = \mathtt{arg}(\mu A_b)$ (radians) and M_{SUSY} (GeV), changing from 300 GeV to 600 GeV.

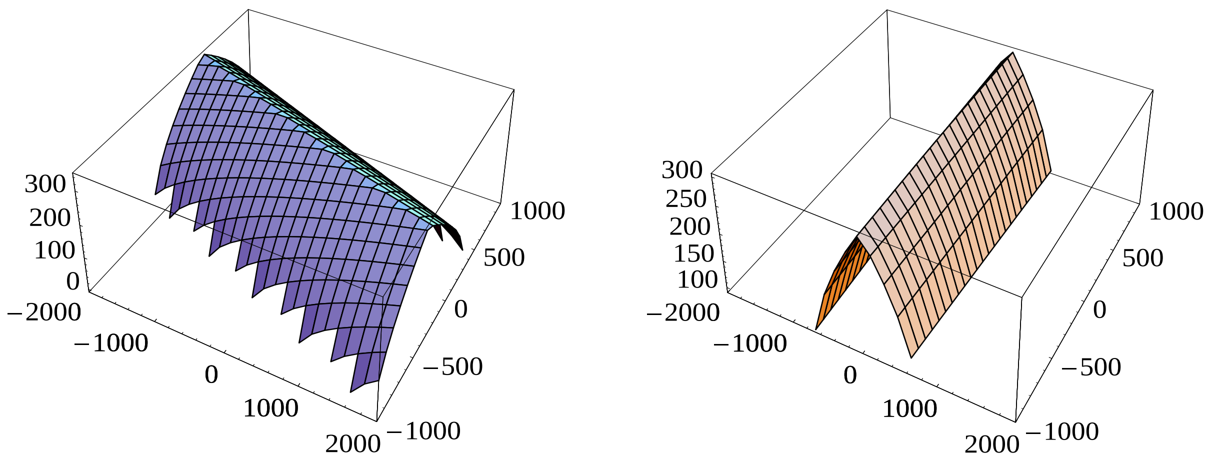


Figure 3: Stop mass m_{t_1} (the left figure for $\mathtt{tg}\beta$ =5) and sbottom mass m_{b_1} (the right figure for $\mathtt{tg}\beta$ =40) vs μ changing from -2 TeV to +2 TeV and $|A_t| = |A_b|$ changing in the interval [-1 TeV, 1 TeV]; M_{SUSY} = 300 GeV, the phase is taken at $\varphi = \mathtt{arg}(\mu A_t) = \mathtt{arg}(\mu A_b) = \pi$.

two mass eigenstates determined by the degree of the mixing and different behaviour of each state decay modes with the phase. For example, the decay $h_2 \to h_1 h_1$ (which is the CP-odd Higgs state decay in the CP conserving limit) is suppressed for vanishing phase and becomes dominant for some nontrivial values of the phase φ in the CP noninvariant MSSM. Furthermore, new decay modes of h_2 and h_3 may be opened with the scalar-pseudoscalar HA mixing in comparison with the CP conserving limit, when they are not allowed due to strict conservation of CP parity.

The decay width $h_i \to H^+ H^-$

$$\Gamma_{h_i \to H^+ H^-} = \sqrt{1 - (4\, m^2_{H^\pm}/m^2_{h_i})}\; \frac{(v\, g_{H^+ H^- h_i})^2}{16\, \pi\, m_{h_i}} \tag{9}$$

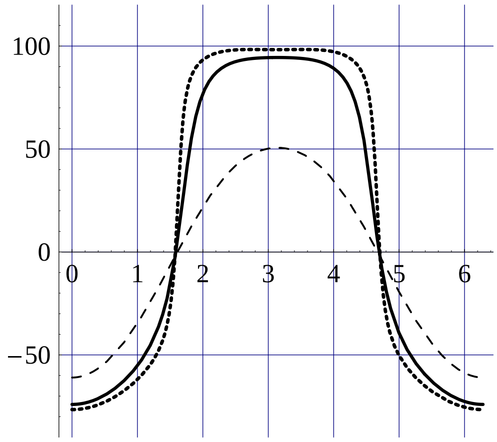


Figure 4: Triple Higgs boson interaction vertex $v \cdot g_{H^+\,H^-\,h_1}$ (GeV) vs the phase $\mathtt{arg}(\mu A)$ in the effective one-loop approximation at the parameter values M_{SUSY} = 500 GeV, $\mathtt{tg}\beta$ =5, $A_{t,b}$ =1000 GeV, μ = 2000 GeV. Long dashed line – $m_{H^\pm}$ = 300 GeV, solid line – $m_{H^\pm}$ = 200 GeV, short dashed line – $m_{H^\pm}$ = 190 GeV.

	SUSY	$\varphi = 0$	$\pi/6$	$\pi/3$	$\pi/2$	$2\pi/3$	$5\pi/6$	π
$g_{h_1h_1h_1}$	–0.34	–0.56	–0.59	–0.65	–0.70	–0.66	–0.55	–0.49
$g_{h_1h_1h_2}$	–0.17	–0.36	0.17	0.12	–0.07	–0.35	–0.61	–0.71
$g_{h_1h_1h_3}$	0	0	0.30	0.29	0.28	0.24	0.15	0
$g_{h_1h_2h_2}$	0.06	–0.22	–0.01	0.20	0.46	0.64	0.70	0.70
$g_{h_1h_2h_3}$	0	0	–0.04	–0.03	–0.02	0.01	0.02	0
$g_{h_1h_3h_3}$	0.12	–0.07	–0.18	–0.11	0.01	0.14	0.23	0.27
$g_{h_2h_2h_2}$	0.15	0.70	–0.68	–0.96	–1.04	–0.92	–0.75	–0.68
$g_{h_2h_2h_3}$	0	0	–0.16	–0.11	–0.09	–0.07	–0.04	0
$g_{h_2h_3h_3}$	0.05	0.24	–0.22	–0.31	–0.35	–0.34	–0.31	–0.30
$g_{h_3h_3h_3}$	0	0	–0.45	–0.28	–0.18	–0.12	–0.06	0

Table 1: The effective trilinear couplings $g_{h_ih_jh_k}$ vs the phase $\varphi = \mathtt{arg}\,(\mu A_{\,t,b})$ at the one-loop and the one-loop with leading two-loop corrections to parameters λ_i included. $G_F = 1.174 \cdot 10^{-5}$ GeV^{-2}, $\alpha_{EM}(m_Z) = 0.007812$, $\alpha_S(m_Z) = 0.1172$, $\mathtt{tg}\beta = 5$, $M_{SUSY} = 500$ GeV, $|A_t| = |A_b| = A = 1000$ GeV, $|\mu| = 2000$ GeV, $m_{H^\pm} = 300$ GeV.

5 Summary

The structure of Higgs boson self-interactions in the theories with explicitly CP violating potentials is extremely strongly sensitive to radiative corrections and the phase of effective parameters. Some detailed numerical evaluations illustrating this sensitivity were performed in the framework of the CPX scenario. The calculation of the trilinear Higgs boson self-couplings $g_{h_1H^+H^-}$ and $g_{h_1h_2h_2}$ with the $h_2 \to h_1h_1$ decay width at the one- and two-loop level demonstrate changes of the couplings in sign at the phase $\sim \pi/2$ and in the absolute value by a factor of 3–5 in comparison with the CP conserving limit, the magnitude of this factor depending essentially on the value taken for the phase of $\lambda_{5,6,7}$ parameters. For example, at moderate $m_{H^\pm}$ the decay $h_2 \to h_1h_1$ is sensitively suppressed at the two-loop level of precision by the kinematical restriction $m_{h_2} < 2m_{h_1}$.

Acknowledgments

	SUSY	$\varphi = 0$	$\pi/6$	$\pi/3$	$\pi/2$	$2\pi/3$	$5\pi/6$	π
$g_{h_1h_1h_1h_1}$	–0.33	–0.53	–0.56	–0.63	–0.69	–0.62	–0.47	–0.38
$g_{h_1h_1h_1h_2}$	–0.17	–0.34	0.17	0.12	–0.08	–0.41	–0.71	–0.83
$g_{h_1h_1h_1h_3}$	0	0	0.29	0.28	0.28	0.25	0.15	0
$g_{h_1h_1h_2h_2}$	0.05	–0.26	–0.04	0.17	0.47	0.72	0.81	0.82
$g_{h_1h_1h_2h_3}$	0	0	–0.06	–0.06	–0.04	–0.01	0.01	0
$g_{h_1h_1h_3h_3}$	0.11	–0.09	–0.21	–0.13	0.01	0.16	0.28	0.32
$g_{h_1h_2h_2h_2}$	0.17	0.46	–0.58	–0.90	–1.06	–0.99	–0.82	–0.74
$g_{h_1h_2h_2h_3}$	0	0	–0.10	–0.06	–0.06	–0.05	–0.03	0
$g_{h_1h_2h_3h_3}$	0.06	0.17	–0.18	–0.29	–0.35	–0.37	–0.34	–0.33
$g_{h_1h_3h_3h_3}$	0	0	–0.26	–0.13	–0.08	–0.06	–0.03	0
$g_{h_2h_2h_2h_2}$	–0.33	2.69	2.46	2.14	1.56	0.94	0.52	0.38
$g_{h_2h_2h_2h_3}$	0	0	0.06	0.07	0.06	0.04	0.02	0
$g_{h_2h_2h_3h_3}$	–0.11	0.86	0.82	0.71	0.54	0.36	0.24	0.20
$g_{h_2h_3h_3h_3}$	0	0	0.06	0.07	0.06	0.05	0.03	0
$g_{h_3h_3h_3h_3}$	–0.35	2.48	2.47	2.09	1.65	1.25	0.98	0.89

Table 2: The effective couplings $g_{h_ih_jh_kh_l}$ vs the phase $\varphi = \texttt{arg}\,(\mu A_{t,b})$, at the one-loop and the one-loop with leading two-loop corrections to parameters λ_i included. $G_F = 1.174 \cdot 10^{-5}$ GeV^{-2}, $\alpha_{EM}(m_Z) = 0.007812$, $\alpha_S(m_Z) = 0.1172$, $\texttt{tg}\beta = 5$, $M_{SUSY} = 500$ GeV, $|A_t| = |A_b| = A = 1000$ GeV, $|\mu| = 2000$ GeV, $m_{H^\pm} = 300$ GeV.

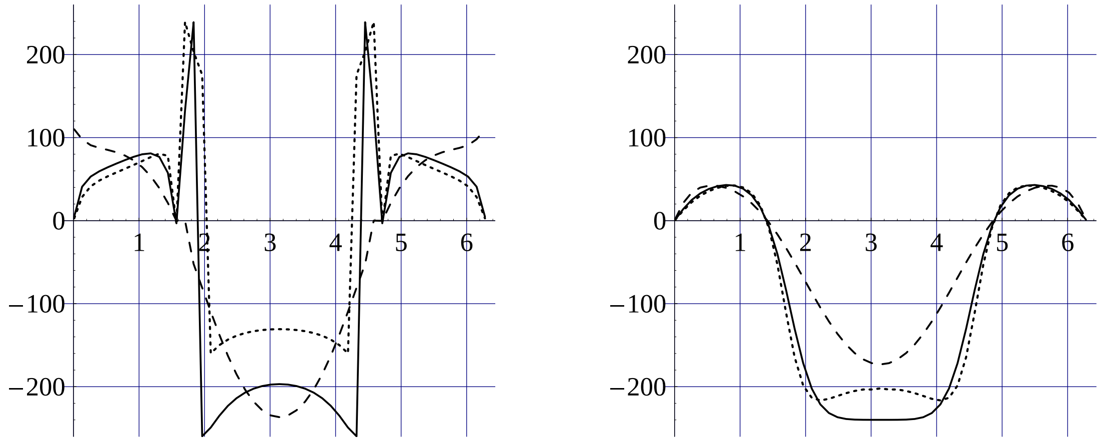
	SUSY	$\varphi = 0$	$\pi/6$	$\pi/3$	$\pi/2$	$2\pi/3$	$5\pi/6$	π
$g_{h_1H^+H^-}$	–0.10	–0.21	–0.19	–0.12	–0.03	0.06	0.12	0.14
$g_{h_2H^+H^-}$	0.05	0.23	–0.22	–0.31	–0.35	–0.35	–0.33	–0.32
$g_{h_3H^+H^-}$	0	0	–0.15	–0.09	–0.06	–0.03	–0.02	0
$g_{h_1h_1H^+H^-}$	–0.10	–0.22	–0.20	–0.13	–0.02	0.09	0.16	0.19
$g_{h_1h_2H^+H^-}$	0.05	0.15	–0.19	–0.29	–0.36	–0.38	–0.36	–0.35
$g_{h_1h_3H^+H^-}$	0	0	–0.09	–0.04	–0.02	–0.01	–0.01	0
$g_{h_2h_2H^+H^-}$	–0.11	0.86	0.80	0.69	0.53	0.36	0.24	0.20
$g_{h_2h_3H^+H^-}$	0	0	0.02	0.02	0.02	0.02	0.01	0
$g_{h_3h_3H^+H^-}$	–0.12	0.83	0.80	0.69	0.55	0.42	0.33	0.30
$g_{H^+H^-H^+H^-}$	–0.24	1.65	1.57	1.36	1.08	0.83	0.65	0.59

Table 3: The effective coulings $g_{h_iH^+H^-}$, $g_{h_ih_jH^+H^-}$ $g_{H^+H^-H^+H^-}$ vs the phase $\varphi = \texttt{arg}\,(\mu A_{t,b})$, at the one-loop and the one-loop with leading two-loop corrections to parameters λ_i included. $G_F = 1.174 \cdot 10^{-5}\,$GeV^{-2}, $\alpha_{EM}(m_Z) = 0.007812$, $\alpha_S(m_Z) = 0.1172$, $\texttt{tg}\beta = 5$, $M_{SUSY} = 500\,$GeV, $|A_t| = |A_b| = A = 1000\,$GeV, $|\mu| = 2000\,$GeV, $m_{H^\pm} = 300\,$GeV.

E. Akhmetzyanova thanks the "Dynasty" foundation and ICPPM for partial financial support. The work of M. Dolgopolov and M. Dubinin was partially supported by RFBR grant 04-02-17448. The work of M. Dubinin was partially supported by INTAS 03-51-4007, UR 02.03.028 and NS 1685.2003.2.

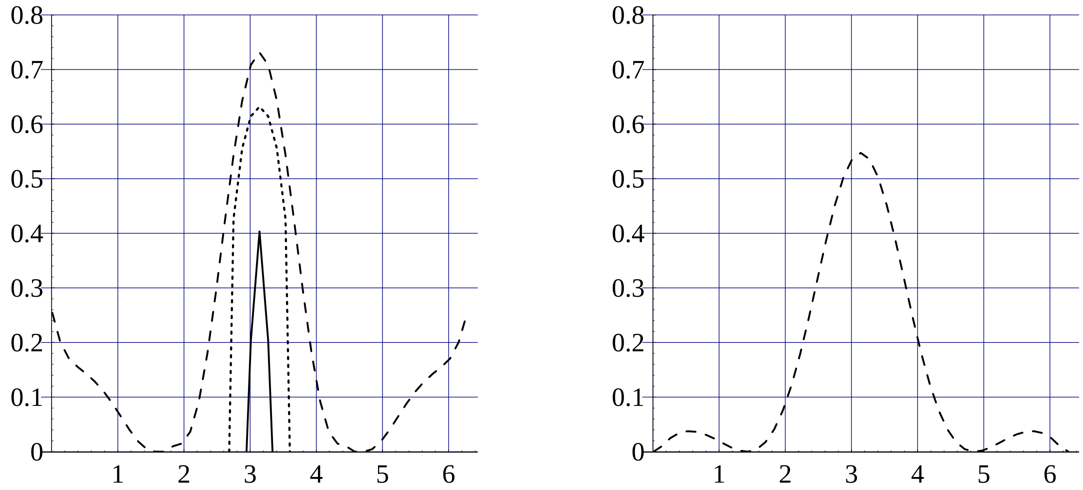
References

[1] I. Ginzburg, M. Krawczyk, hep-ph/0408011
S.Y. Choi, J. Kalinowski, Y. Liao, P.M. Zerwas, Eur.Phys.J. **C40** (2005) 555
M. Carena, J. Ellis, A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. **B625** (2002) 345
S. Heinemeyer, Eur. Phys. J. **C22** (2001) 521



(a) (b)

Figure 5: Light Higgs boson interaction vertex $v \cdot g_{h_1 h_1 h_2}$ (GeV) vs the phase $\mathtt{arg}(\mu A)$ at parameter values $M_{SUSY} = 500\,\mathrm{GeV}$, $\mathtt{tg}\beta = 5$, $A_{t,b} = 1000\,\mathrm{GeV}$, $\mu = 2000\,\mathrm{GeV}$. Long dashed line – $m_{H^\pm} = 300\,\mathrm{GeV}$, solid line – $m_{H^\pm} = 200\,\mathrm{GeV}$, short dashed line – $m_{H^\pm} = 190\,\mathrm{GeV}$. (a) – effective one-loop approach, (b) – with leading two-loop corrections.



(a) (b)

Figure 6: The decay width $h_2 \to h_1 h_1$ (GeV) vs the phase $\mathtt{arg}(\mu A)$ at parameter values $M_{SUSY} = 500$ GeV, $\mathtt{tg}\beta = 5$, $A_{t,b} = 1000$ GeV, $\mu = 2000$ GeV. Long dashed line – $m_{H^\pm} = 300$ GeV, solid line – $m_{H^\pm} = 200$ GeV, short dashed line – $m_{H^\pm} = 190$ GeV. (a) – effective one-loop approach, (b) – with leading two-loop corrections.

S.Y. Choi, J.S. Lee, Phys. Rev. **D61** (2000) 015003
S.Y. Choi, M. Drees, J.S. Lee, Phys. Lett. **B481** (2000) 57
D.A. Demir, Phys. Rev. **D60** (1999) 055006
[2] A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. **B553** (1999) 3
[3] E. Akhmetzyanova, M. Dolgopolov, M. Dubinin, Phys.Rev. **D71** (2005) 075008
[4] H.E. Haber, R. Hempfling, Phys. Rev. **D48** (1993) 4280
[5] M.N. Dubinin, A.V. Semenov, Eur. J. Phys. **C28** (2003) 223

[6] J.S. Lee, A. Pilaftsis, M. Carena, S.Y. Choi, M. Drees, J.R. Ellis, C.E.M. Wagner, Comput.Phys.Commun. **156** (2004) 283

[7] S. Heinemeyer, hep-ph/0407244
M. Frank, S. Heinemeyer, W. Hollik, G. Weiglein, hep-ph/0212037
S. Heinemeyer, W. Hollik, G. Weiglein, hep-ph/9812320

[8] M. Moretti, S. Moretti, F. Piccinini, R. Pittau, A.D. Polosa, JHEP 0502 (2005) 024
S.W. Ham, S.K. Oh, hep-ph/0502116
S. Kanemura, Y. Okada, E. Senaha, Phys.Lett. **B606**(2005) 361
S. Kanemura, Y. Okada, E. Senaha, C.-P. Yuan, Phys.Rev. **D70** (2004) 115002
J.F. Gunion, H.E. Haber, Phys. Rev. **D67** (2003) 075019
F. Boudjema, A. Semenov, Phys. Rev. **D66** (2002) 095007
S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha, C.-P. Yuan, Phys.Lett. **B558** (2003) 157

[9] S.Y. Choi, J. Kalinowski, hep-ph/0508121
S.Heinemeyer, M. Velasco, hep-ph/0506267
A.G. Akeroyd, S. Kanemura, Y. Okada, E. Senaha, hep-ph/0409318

[10] M. Carena, J. Ellis, S. Mrenna, A. Pilaftsis, C.E.M. Wagner, Nucl. Phys. **B659** (2003) 145
R.M. Godbole, S.D. Rindani, R.K. Singh, Phys. Rev. **D67** (2003) 095009
A. Dedes, S. Moretti, Nucl. Phys. **B576** (2000) 29
B. Grzadkowski, J.F. Gunion, J. Kalinowski, Phys. Rev. **D60** (1999) 075011
P. Osland, P.N. Pandita, Phys.Rev. **D59** (1999) 55013
A. Djouadi, W. Kilian, M. Muhlleitner, P.M. Zerwas, Eur.Phys.J. **C10** (1999) 27
A. Djouadi, H.E. Haber, P.M. Zerwas, Phys.Lett. **B375** (1996) 203

[11] M. Carena, J. Ellis, A. Pilaftsis, C. Wagner, Phys.Lett. **B495** (2000) 155