Self-couplings of Higgs bosons in supersymmetric models with CP-violation

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1. Minimal supersymmetric standard model
   - Effective potential of MSSM
   - Parameters of Effective Potential of MSSM
   - Self-couplings of Higgs bosons in MSSM

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Effective potential of MSSM

In two-doublet model there are two identical $SU(2)$ doublets of complex scalar fields Φ_1 and Φ_2

$$\Phi_1 = \begin{pmatrix} \phi_1^+(x) \\ \phi_1^0(x) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+(x) \\ \phi_2^0(x) \end{pmatrix}$$

with nonzero vacuum expectation values

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}.$$

Neutral components of doublets

$$\phi_1^0(x) = \frac{1}{\sqrt{2}}(v_1 + \eta_1 + i\chi_1), \;\; \phi_2^0(x) = \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i\chi_2).$$

Effective potential

The most general renormalizable hermitian $SU(2) \times U(1)$ invariant potential:

$$U(\Phi_1, \Phi_2) = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \mu_{12}^2(\Phi_1^\dagger\Phi_2) - \overset{*}{\mu_{12}^2}(\Phi_2^\dagger\Phi_1) +$$

$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) +$$

$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \frac{\overset{*}{\lambda_5}}{2}(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) +$$

$$+\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \overset{*}{\lambda_6}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) +$$

$$+\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \overset{*}{\lambda_7}(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

with effective real parameters μ_1^2, μ_2^2, λ_1,...,λ_4 and complex parameters μ_{12}^2, λ_5, λ_6, λ_7.

Parameters of Effective Potential of MSSM

In the tree approximation on the energy scale M_{SUSY}, the parameters λ_{1-7} are real and are expressed using the coupling constants g_1 and g_2 of electroweak group of the gauge symmetry $SU(2) \otimes U(1)$ as follows:

$$\lambda_1(M_{SUSY}) = \lambda_2(M_{SUSY}) = \frac{1}{4}\left(g_2^2(M_{SUSY}) + g_1^2(M_{SUSY})\right),$$

$$\lambda_3(M_{SUSY}) = \frac{1}{4}\left(g_2^2(M_{SUSY}) - g_1^2(M_{SUSY})\right),$$

$$\lambda_4(M_{SUSY}) = -\frac{1}{2}g_2^2(M_{SUSY}),$$

$$\lambda_5(M_{SUSY}) = \lambda_6(M_{SUSY}) = \lambda_7(M_{SUSY}) = 0.$$

Parameters of Effective Potential of MSSM

The supersymmetric scalar potential of interaction of Higgs bosons with the third generation quark superpartners on the tree level has the form

$$\mathcal{V}^0 = \mathcal{V}_M + \mathcal{V}_\Gamma + \mathcal{V}_\Lambda + \mathcal{V}_{\widetilde{Q}} \,,$$

$$\mathcal{V}_M = (-1)^{i+j} m_{ij}^2 \Phi_i^\dagger \Phi_j + M_{\widetilde{Q}}^2 \left(\widetilde{Q}^\dagger \widetilde{Q}\right) + M_{\widetilde{U}}^2 \widetilde{U}^* \widetilde{U} + M_{\widetilde{D}}^2 \widetilde{D}^* \widetilde{D} \,,$$

$$\mathcal{V}_\Gamma = \Gamma_i^D \left(\Phi_i^\dagger \widetilde{Q}\right) \widetilde{D} + \Gamma_i^U \left(i\Phi_i^T \sigma_2 \widetilde{Q}\right) \widetilde{U} + \overset{*}{\Gamma}{}_i^D \left(\widetilde{Q}^\dagger \Phi_i\right) \widetilde{D}^* - \overset{*}{\Gamma}{}_i^U \left(i\widetilde{Q}^\dagger \sigma_2 \Phi_i^*\right) \widetilde{U}^* \,,$$

$$\mathcal{V}_\Lambda = \Lambda_{ik}^{jl} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_k^\dagger \Phi_l\right) + \left(\Phi_i^\dagger \Phi_j\right) \left[\Lambda_{ij}^Q \left(\widetilde{Q}^\dagger \widetilde{Q}\right) + \Lambda_{ij}^U \widetilde{U}^* \widetilde{U} + \Lambda_{ij}^D \widetilde{D}^* \widetilde{D}\right] +$$

$$+\overline{\Lambda}{}_{ij}^Q \left(\Phi_i^\dagger \widetilde{Q}\right) \left(\widetilde{Q}^\dagger \Phi_j\right) + \frac{1}{2} \left[\Lambda \epsilon_{ij} \left(i\Phi_i^T \sigma_2 \Phi_j\right) \widetilde{D}^* \widetilde{U} + \text{э.c.}\right] \,, i, j, \, k, l = 1, 2 \,,$$

$\mathcal{V}_{\widetilde{Q}}$ denotes the terms of interaction of four scalar quarks.

Self-couplings of Higgs bosons in MSSM

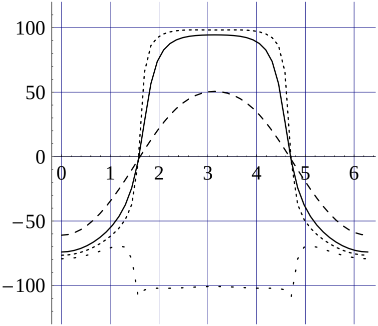
The effective trilinear, $g_{h_i h_j h_k}$, and the quartic, $g_{h_i h_j h_k h_l}$, couplings of physical Higgs self-interactions in the THDM can be written in the following compact forms:

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

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

$$+ \frac{1}{4} g_{H^+ H^- H^+ H^-} (H^+ H^-)^2.$$

Self-couplings of Higgs bosons in MSSM



The triple Higgs boson interaction vertex $v \cdot g_{H^+\,H^-\,h_1}$ (GeV) vs the phase $\mathrm{Arg}(\mu A)$ for 1-loop approximation to lambda-couplings at $M_{SUSY} = 500$ GeV, tgβ =5, $A_{t,b}$ =1000 GeV, $\mu = 2000$ GeV.

Effective potential of NMSSM

In the NMSSM two identical scalar $SU(2)$ doublets of the complex scalar fields Φ_1 and Φ_2 are introduced

$$\Phi_1 = \begin{pmatrix} \phi_1^+(x) \\ \phi_1^0(x) \end{pmatrix} = \begin{pmatrix} -i\omega_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \eta_1 + i\chi_1) \end{pmatrix},$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+(x) \\ \phi_2^0(x) \end{pmatrix} = \begin{pmatrix} -i\omega_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i\chi_2) \end{pmatrix}$$

Singlet superfield S:

$$S = \frac{1}{\sqrt{2}}(v_3 + s_1 + is_2).$$

Effective potential of NMSSM

The most general Hermitian form of the renormalized $SU(2) \times U(1)$ invariant potential for system of fields has the form:

$$U(\Phi_1, \Phi_2, S) = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \mu_3^2 S^* S - \mu_{12}^2(\Phi_1^\dagger\Phi_2) - \overset{*}{\mu}{}_{12}^{2}(\Phi_2^\dagger\Phi_1)$$

$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) +$$

$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \frac{\overset{*}{\lambda}_5}{2}(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) +$$

$$+\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \overset{*}{\lambda}_6(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \overset{*}{\lambda}_7(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

$$+k_1(\Phi_1^\dagger\Phi_1)S^*S + k_2(\Phi_2^\dagger\Phi_2)S^*S + k_3(\Phi_1^\dagger\Phi_2)S^*S + \overset{*}{k}_3(\Phi_2^\dagger\Phi_1)S^*S + k_4(S^*S)^2 +$$

$$+k_5(\Phi_1^\dagger\Phi_1)S + k_6(\Phi_2^\dagger\Phi_2)S + k_7(\Phi_1^\dagger\Phi_2)S + \overset{*}{k}_7(\Phi_2^\dagger\Phi_1)S^* + k_8 S^3.$$

Parameters of Effective Potential of NMSSM

In the tree approximation on the energy scale M_{SUSY}, the parameters λ_i, κ_j expressed as:

$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{8},\ \lambda_3 = \frac{g_2^2 - g_1^2}{4},\ \lambda_4 = -\frac{g_2^2}{2}, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0 \quad (1)$$

$$k_1 = |\lambda|^2,\ \ k_2 = |\lambda|^2,\ \ k_3 = \lambda k^*,\ \ k_4 = |k|^2,\ \ k_5 = \lambda A_\lambda,\ \ k_6 = \frac{1}{3} k A_k, \quad (2)$$

The free parameters of the model are chosen in the range possible values:

$$1.0 < tg\beta \leq 60, \quad M_1 = M_2, \quad 100\,\mathrm{GeV} \leq M_2 \leq 2000\,\mathrm{GeV},$$

$$0.0001 \leq \lambda \leq 0.7, \quad 0 \leq \kappa \leq 0.65.$$

$$0\,\mathrm{GeV} \leq A_\lambda \leq 1000\,\mathrm{GeV}, \quad -100\,\mathrm{GeV} \leq A_\kappa \leq -10\,\mathrm{GeV}$$

Parameters of Effective Potential of NMSSM

The supersymmetric scalar potential of interaction of Higgs bosons with the third generation quark superpartners on the tree level has the form

$$V = |y_u(\widetilde{Q}\epsilon H_u)|^2 + |y_d(\widetilde{Q}\epsilon H_d)|^2 + |y_u \widetilde{u}_R^* H_u^0 - y_d \widetilde{d}_R^* H_d^-|^2 + |y_d \widetilde{d}_R^* H_d^0 - y_d \widetilde{u}_R^* H_u^+|^2 -$$

$$- y_u(\widetilde{u}_R \widetilde{u}_L^* \lambda S H_d^0 + \widetilde{u}_R \widetilde{d}_L^* \lambda S H_d^- + c.c.) - y_d(\widetilde{d}_R \widetilde{d}_L^* \lambda S H_u^0 + \widetilde{d}_R \widetilde{d}_L^* \lambda S H_u^+ + c.c.) +$$

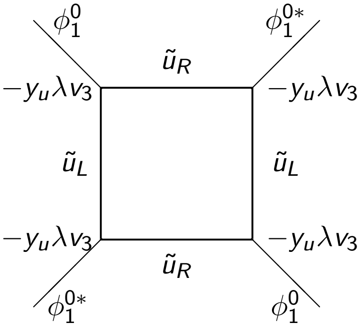
$$+ \frac{g_2^2}{8}(4|H_d^\dagger \widetilde{Q}|^2 - 2(H_d^\dagger H_d)(\widetilde{Q}^\dagger \widetilde{Q}) + 4|H_u^\dagger \widetilde{Q}|^2 - 2(H_u^\dagger H_u)(\widetilde{Q}^\dagger \widetilde{Q})) +$$

$$+ \frac{g_1^2}{2}(\frac{1}{6}(\widetilde{Q}^\dagger \widetilde{Q}) - \frac{2}{3}\widetilde{u}_R^* \widetilde{u}_R + \frac{1}{3}\widetilde{d}_R^* \widetilde{d}_R + \frac{1}{2}(H_u^\dagger H_u) - \frac{1}{2}(H_d^\dagger H_d))^2 +$$

$$+ (\widetilde{u}_R^* y_u A_u (\widetilde{Q}^T \epsilon H_u) - \widetilde{d}_R y_d A_d (\widetilde{Q}^T \epsilon H_d) + c.c.)$$

Parameters of Effective Potential of NMSSM

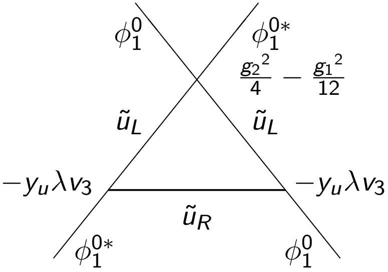
The oneloop corrections to the parameters of effective potential



$$(y_u\lambda v_3)^4 I_2[m_Q, m_U]$$

Parameters of Effective Potential of NMSSM

The oneloop corrections to the parameters of effective potential



$$(-y_u\lambda v_3)^2\left(\frac{g_2{}^2}{4} - \frac{g_1{}^2}{12}\right)I_1[m_Q, m_U]$$

Parameters of Effective Potential of NMSSM

The oneloop corrections to the parameters of effective potential

$$\Delta\lambda_1 = h_u^4\lambda^4 v_3^4 I_2[m_Q, m_U] + h_d^4 A_d^4 I_2[m_Q, m_D] +$$

$$+h_u^2\lambda^2 v_3^2\left(\left(\frac{g_2^2}{4} - \frac{g_1^2}{12}\right) I_1[m_Q, m_U] + \frac{1}{3}g_1^2 I_1[m_U, m_Q]\right) +$$

$$+h_d^2 A_d^2\left(\left(h_d^2 - \frac{g_1^2}{12} - \frac{g_2^2}{4}\right) I_1[m_Q, m_D] + \left(h_d^2 - \frac{g_1^2}{6}\right) I_1[m_D, m_Q]\right)$$

$$\Delta\lambda_2 = h_u^4 A_u^4 I_2[m_Q, m_U] + h_d^4\lambda^4 v_3^4 I_2[m_Q, m_D] +$$

$$+h_u^2 A_u^2\left(\left(\frac{g_1^2}{12} - \frac{g_2^2}{4}\right) I_1[m_Q, m_U] + (h_u^2 - \frac{1}{3}g_1^2 I_1[m_U, m_Q]\right) +$$

$$+h_d^2\lambda^2 v_3^2\left(\left(\frac{g_1^2}{12} + \frac{g_2^2}{4}\right) I_1[m_Q, m_D] + \frac{g_1^2}{6} I_1[m_D, m_Q]\right)$$

Higgs bosons masses in NMSSM

Mass matrix of the Higgs bosons:

$$m^2 = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} \\ m_{31} & m_{32} & m_{33} & m_{34} & m_{35} \\ m_{41} & m_{42} & m_{43} & m_{44} & m_{45} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} \end{pmatrix},$$

and its elements are defined as the second derivatives of the Higgs potential $m_{ij} = \frac{\partial^2 V}{\partial\phi_i \partial\phi_j}$

$$m_{11} = \frac{1}{4} v^2 (\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + 2\sin^2\beta\cos^2\beta(-Im\lambda_5 \sin(2\theta) + \lambda_3 +$$
$$+\lambda_4 - Re\lambda_5 \cos(2\theta)) + 4\sin\beta\cos^3\beta(Re\lambda_6 \sin\theta - Im\lambda_6 \cos\theta) +$$
$$+4\sin^3\beta\cos\beta(Re\lambda_7 \sin\theta - Im\lambda_7 \cos\theta))$$

Self-couplings of Higgs bosons in the NMSSM

The effective trilinear, $g_{h_i h_j h_k}$, and the quartic, $g_{h_i h_j h_k h_l}$, couplings of physical Higgs self-interactions in the NMSSM can be written in the following compact forms::

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

$$\mathcal{L}_{4H} = \sum_{i \geq j \geq k \geq l = 1}^{3} g_{h_i h_j h_k h_l} \frac{1}{N_S} h_i h_j h_k h_l + \sum_{i \geq j = 1}^{3} g_{h_i h_j H^+ H^-} \frac{1}{N_S} h_i h_j H^+ H^- +$$
$$+ \frac{1}{4} g_{H^+ H^- H^+ H^-} (H^+ H^-)^2 .$$

Conclusion

- One-loop corrections to the parameters of the effective potential in the case of different masses of scalar quarks in MSSM and NMSSM are obtained.
- Diagonalization of the mass matrix 5x5 are carried out, mass state of the neutral Higgs bosons in NMSSM with CP violation are received .
- Self-couplings of Higgs bosons in supersymmetric models with CP-violation are obtained.
- The investigation of the self-couplings of the Higgs bosons in NMSSM and the relationship of the results for the self-couplings of the Higgs bosons with the experimental constraints are performed.