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Higgs bosons in NMSSM with CP-violation

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The CP-violation problem

[1] Christenson J. H. Evidence for the 2p decay of the K0 2 meson / J. H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay // Phys. Rev. Lett. - 1964. - V.13. - P.138-140.

[2] Sakharov A.D. Violation of CP invariance, C-asymmetry and baryon asymmetry of the Universe // Pisma v ZhETF [Letters to the Journal of Experimental and Theoretical Physics], 1967, Vol. 5, Issue 1, pp. 32–35. [in Russian]

The Sakharov conditions for baryon asymmetry:

- the violation of baryon number;
- C-violation and CP-violation;
- the deviation from thermodynamic.

The CP-violation problem

[3] Kobayashi M., Maskawa T. CP Violation in the Renormalizable Theory of Weak Interaction // Prog. Theor. Phys.–1973.–V. 49.– P. 652-657.

Matrix CKM: $\hat{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$

$$= \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}\mathbf{e}^{\mathbf{i}\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}\mathbf{e}^{\mathbf{i}\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}\mathbf{e}^{\mathbf{i}\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}\mathbf{e}^{\mathbf{i}\delta} & -S_{23}C_{12} - S_{12}C_{23}S_{13}\mathbf{e}^{\mathbf{i}\delta} & C_{23}C_{13} \end{pmatrix},$$

where $C_{ij} = \cos\Theta_{ij}, S_{ij} = \sin\Theta_{ij}, \delta-$complex phase.

[4] Gavela M.B. Standard model CP-violation and baryon asymmetry (II). Finite temperature / M.B. Gavela [et al.] // Nucl.Phys.B. - 1994. - V.430. - P.382-426.

Matrix CKM is not enough to describe the baryon asymmetry!

The CP-violation problem

CP-violation in the lepton sector:

[5] Connecting Leptonic CP Violation, Lightest Neutrino Mass and Baryon Asymmetry Through Type II Seesaw // Int. J. Mod. Phys. A – 2015. – V.

[6] Petcov S.T. Leptonic CP violation and leptogenesis // Int. J. Mod. Phys.A – 2014.– V.30.–19P.

... etc.

CP-violation in the extended Higgs sector:

[7] Pilaftsis A., WagnerC.E.M. Higgs Bosons in the Minimal Supersyminetry Standard Model with Explicit CP Violation // Nucl. Phys. B. 1999. V. 553. P. 3-42.

[8] Choi S. K, Lee J.S. Decays of the MSSM Higgs Bosons with Explicit CP-Violation // Phys. Rev. D. 2000. V. Gl. P. 015003.

[9] Carena M. et al Higgs-Boson Pole Masses in the MSSM with Explicit CP Violation // NucL Phys. B. 2002. 625. P. 345-371.

The CP-violation problem

CP-violation in the extended Higgs sector:

[10] Akhmetzyanova E.N., Dolgopolov M.V., Dubinin M.N. Higgs Bosons in the Two-Doublet Model with CP Violation // Phys.Rev.D. V.71. N7. 2005. P.075008

[11] Akhmetzyanova E.N., Dolgopolov M.V., Dubinin M.N., Smirnov I.A., Shcherbakova E. S. Supersymmetric model with violation of CP invariance. 1. The decays of the Higgs boson $h \to gg$ и $h \to \gamma\gamma$ // Vestnik SamGU, 2003. N 2(28). C.122-136.

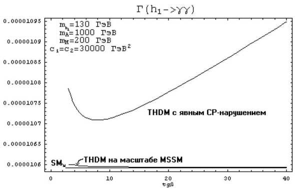

Fig.1. The dependence of the decay widths from $\tan\beta$ [11].

[12] Akhmetzyanova E. N., Dolgopolov M. V., Dubinin M. N. Supersymmetric model with violation of CP invariance. 3. The violation of CP invariance in the Higgs sector // Vestnik SamGU, 2003. N 4(30). P. 147-179.

... etc.

Models with the extended Higgs sector

	superfield	SM field	spin	superpartner	spin
quarks/	$\hat{Q}$	$Q = \begin{pmatrix} U_\alpha \\ D_\alpha \end{pmatrix}_L$	$\frac{1}{2}$	$\tilde{Q} = \begin{pmatrix} \tilde{U}_\alpha \\ \tilde{D}_\alpha \end{pmatrix}_L$	0
squarks	$\hat{U}$	$U_{\alpha R}$	$\frac{1}{2}$	$\tilde{U}_{\alpha R}$	0
	$\hat{D}$	$D_{\alpha R}$	$\frac{1}{2}$	$\tilde{D}_{\alpha R}$	0
leptons/	$\hat{L}$	$L_{\alpha L}$	$\frac{1}{2}$	$\tilde{L}_{\alpha L}$	0
sleptons	$\hat{E}$	$E_{\alpha R}$	$\frac{1}{2}$	$\tilde{E}_{\alpha R}$	0
gauge	$\hat{G}$	G^a_μ	1	$\tilde{G}^a_\mu$	$\frac{1}{2}$
bosons /	$\hat{W}$	$W^\pm$, W^0	1	$\tilde{W}^\pm$, $\tilde{W}^0$	$\frac{1}{2}$
gaugino	$\hat{B}$	B^0	1	$\tilde{B}^0$	$\frac{1}{2}$
Higgs/	$\hat{H}_1$	$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$	0	$\tilde{H}_1 = \begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}$	$\frac{1}{2}$
higgsino,	$\hat{H}_2$	$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$	0	$\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}$	$\frac{1}{2}$
S field/ singlino	$\hat{S}$	S	0	$\tilde{S}$	$\frac{1}{2}$

models	2HDM	MSSM	**NMSSM**
physical Higgs states	2 neutral CP-even 1 neutral CP-odd 2 charged	2 neutral CP-even 1 neutral CP-odd 2 charged	3 neutral CP-even 2 neutral CP-odd 2 charged

The NMSSM

Fields can be parameterized:

$$\Phi_1 = \left(\begin{array}{c} \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \\ \phi_1^- \end{array} \right), \ \ \Phi_2 = e^{i\theta} \left(\begin{array}{c} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{array} \right), \tag{1}$$

$$S = \frac{1}{\sqrt{2}} e^{i\varphi}(v_3 + h_3 + ia_3)$$

$$U(\Phi_1, \Phi_2, S) = -\,\mu_1^2(\Phi_1^\dagger \Phi_1) - \,\mu_2^2(\Phi_2^\dagger \Phi_2) - \,\mu_3^2(S^\dagger S) +$$

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

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

$$+\lambda_6(\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) + \lambda_6^*(\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_1) + \lambda_7(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_2) + \lambda_7^*(\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) +$$

$$+k_1(\Phi_1^\dagger \Phi_1)(S^\dagger S) + k_2(\Phi_2^\dagger \Phi_2)(S^\dagger S) + k_3(\Phi_1^\dagger \Phi_2)(S^\dagger S^\dagger) + k_3(\Phi_2^\dagger \Phi_1)(SS) +$$

$$+k_4(S^\dagger S)^2 + k_5(\Phi_1^\dagger \Phi_2)S + k_5(\Phi_2^\dagger \Phi_1)S^\dagger + k_6 S^3 + k_6(S^\dagger)^3$$

Local minimum conditions of the Higgs potential

We should calculate: $\frac{\partial U}{\partial v_1} = 0$, $\frac{\partial U}{\partial v_2} = 0$, $\frac{\partial U}{\partial v_3} = 0$ and obtain equations for: $\mu_1^2, \mu_2^2, \mu_{12}^2$.

$$\mu_1^2 = \frac{1}{2}\left(v^2\lambda_1 \cos^2\beta + v^2(\lambda_3 + \lambda_4 + Re\lambda_5)\sin\beta^2 + v^2\sin\beta(3Re\lambda_6\cos\beta + Re\lambda_7\tan\beta)\right) +$$

$$+\frac{1}{2}k_1 v_3^2 + (\frac{1}{2}Rek_3 v_3 + \frac{1}{\sqrt{2}}Rek_5)v_3\ \tan\beta,$$

$$\mu_2^2 = \frac{1}{2}\left(v^2\lambda_2 \sin^2\beta + v^2(\lambda_3 + \lambda_4 + Re\lambda_5)\cos\beta^2 + v^2\cos\beta(3Re\lambda_7\sin\beta + Re\lambda_6\cot\beta)\right) +$$

$$+\frac{1}{2}k_2 v_3^2 + (\frac{1}{2}Rek_3 v_3 + \frac{1}{\sqrt{2}}Rek_5)v_3\ \cot\beta,$$

$$\mu_3^2 = \frac{v^2}{2}\left(k_1\ \cos^2\beta + k_2\ \sin^2\beta + (Rek_3 + \frac{1}{\sqrt{2}v_3}Rek_5)\ \sin 2\beta\right) + Rek_4\, v_3^2 + \frac{3}{2}Rek_6 v_3.$$

where $v^2 = v_1^2 + v_2^2$, $\tan\beta = v_2/v_1$

If CP invariance is violated, we must consider the matrix 5x5 for which the eigenvalues do not have a definite CP-parity.

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

$$m_{11} = \frac{v^2}{2}(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + 2(\lambda_3 + \lambda_4 + Re\lambda_5)\cos^2\beta\sin^2\beta +$$

$$+4Re\lambda_6\cos^3\beta\sin\beta + 4Re\lambda_7\cos\beta\sin^3\beta),$$

$$m_{12} = \frac{1}{4}(3v^2(Im\lambda_5\sin 2\beta + Im\lambda_6(1+\cos 2\beta) + Im\lambda_7(1-\cos 2\beta))$$

$$-2v_3(v_3 Imk_3 + \sqrt{2}Imk_5)),$$

$$m_{13} = \frac{1}{8}v^2(-\lambda_1(\sin 2\beta + \sin 4\beta) + \lambda_2(\sin 2\beta - \sin 4\beta) + 2(\lambda_3 + \lambda_4 + Re\lambda_5)\sin 4\beta +$$

$$+4(Re\lambda_6(\cos 2\beta + \cos 4\beta) + Re\lambda_7(\cos 2\beta - \cos 4\beta)),$$

$$m_{14} = v(v_3(k_1\cos^2\beta + k_2\sin^2\beta) + (v_3 Rek_3 + \frac{1}{\sqrt{2}}Rek_5)\sin 2\beta),$$

$$m_{15} = v(v_3 Imk_3 - \frac{1}{\sqrt{2}}Imk_5)\sin 2\beta,$$

$$m_{22} = -\frac{1}{8}\left(v^2(2Re\lambda_5\sin 2\beta + Re\lambda_6(1+\cos 2\beta) + Re\lambda_7(1-\cos 2\beta)) +\right.$$

$$\left. + 2v_3(v_3 Rek_3 + \sqrt{2}Rek_5)\right)\csc\beta\sec\beta,$$

$$m_{23} = \frac{1}{2}v^2(Im\lambda_5 \cos 2\beta + (Im\lambda_7 - Im\lambda_6)\sin 2\beta),$$

$$m_{24} = -v(v_3 Imk_3 + \frac{1}{\sqrt{2}}Imk_5), \qquad m_{25} = v(v_3 Rek_3 - \frac{1}{\sqrt{2}}Rek_5),$$

$$m_{33} = \frac{1}{16}\left(v^2(\lambda_1(1-\cos 4\beta) + \lambda_2(1-\cos 4\beta) + 2(\lambda_3 + \lambda_4 + Re\lambda_5)(\cos 4\beta - 1) - \right.$$

$$-(.4(Re\lambda_6(\cot\beta + \sin 4\beta) + Re\lambda_7(\tan\beta - \sin 4\beta))$$

$$-4v_3\left(Rek_3 v_3 + \sqrt{2}Rek_5\right)\csc\beta\sec\beta),$$

$$m_{34} = \frac{1}{2}v\left(v_3(k_2 - k_1)\sin 2\beta + 2\left(v_3 Rek_3 + \frac{1}{\sqrt{2}}Rek_5\right)\cos 2\beta\right),$$

$$m_{35} = v\cos 2\beta\left(v_3 Imk_3 - \frac{1}{\sqrt{2}}Imk_5\right),$$

$$m_{44} = v_3^2 k_4 - \frac{1}{2\sqrt{2}}\left(\frac{v^2}{v_3}Rek_5\sin\beta\cos\beta + 3v_3 Rek_6\right),$$

$$m_{45} = v^2 Imk_3 \sin\beta\cos\beta - 3\sqrt{2}v_3 Imk_6,$$

$$m_{55} = -\frac{1}{4v_3}(v^2(4Rek_3 v_3 + \sqrt{2}Rek_5)\sin\beta\cos\beta + 9\sqrt{2}v_3^2 Rek_6).$$

Free parameters

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

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

$$0\,\text{ГэВ} \leq A_\lambda \leq 1000\,\text{ГэВ}, \quad -100\,\text{ГэВ} \leq A_\kappa \leq -10\,\text{ГэВ}$$

$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{8}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}. \tag{3}$$

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

NMSSM parametrs for Higgs bosons scenario

	CP invariance		CP violation	
Parameters of model \	1	2	3	4
λ	0.002	0.01	0.35	0.14
κ	0.65	0.65	0.36	0.47
$tg\beta$	9.5	1.75	14	50
A_λ, GeV	3	115	1000	100
A_κ, GeV	-100	-100	-100	-100
$m_{h_1} \setminus m_{H_1}$, GeV	125	127	125	46
$m_{h_2} \setminus m_{H_2}$, GeV	127	848	142	125
$m_{a_1} \setminus m_{H_3}$, GeV	121	125	395	424
$m_{\chi_1^0}$, GeV	34	33	103	38

Thank you for your attention!