Higgs bosons in NMSSM with CP-violation

Albina Gurskaya[1]
Samara State University
Akademik Pavlov 1, 443011 Samara, Russia

We review possible scenarios with multiple Higgs bosons in the framework of the NMSSM. The Higgs sector contains CP-violation mechanism. Also, we use local minimum conditions for finding of the Higgs bosons phisical states. Free parameters of the model are defined on some interval of possible values, but each selected value of one of parameters is consistent with several other. Therefore, it makes sense to consider specific scenarios to test the chosen values of parameters.

1 Introduction

CP violation was discovered in the decays of K-mesons in 1964 by V. Fitch and J.Cronin [1]. There is source of CP-violation in the Standard Model (SM). It is the mixing matrix of the fundamental fermions of Cabbibo-Kobayashi-Maskawa(CKM), but this source is not enough to describe the experimental CP violation [2]. Also, according to A. D. Sakharov [3], CP violation is one of the reasons for the predominance of matter over antimatter in the Universe. Again, for explaining of observed value of the baryon asymmetry of the CKM matrix is not enough [4, 5].

There are works [6, 7], and others, devoted to the search of CP violation in the lepton sector, as well as extended scalar sector. The authors of these works consider the extension of the SM, because in addition to the impossibility to explain the baryon asymmetry, SM has other problems that are solved by the inclusion of new fields. Also, the extended Higgs sector can contain additional sources of CP violation. This variant has already been reviewed previously [8–10]. We will consider CP-violation, like the works [11–13].

The violation of CP invariance can be explicit and spontaneous. Explicit violation can be entered through complex parameters in the Higgs potential, or through the complex constants of the interaction of the Higgs boson with particles, for example, Yukawa couplings or constant interaction with gauge bosons. Spontaneous violation arises from the complexity of the vacuum values of the Higgs fields (v_i). In earlier work it was shown that CP violation cannot be spontaneous only, because in this case, the procedure of finding the local minimum of the Higgs potential is incorrect. A local minimum corresponds to the stable state of vacuum, and the procedure of its finding in the Higgs potential is required.

On the one hand, mutual transformation of bosons and fermions gave the opportunity to solve a number of problems related to the calculation of loop contributions to the perturbation theory and some others. Moreover, supersymmetry seems to be quite natural from the point of view of theory development. On the other hand, particles-superpartners not detected in experiment yet. Thus, supersymmetry can not be implemented under the SM due to the mismatch of degrees of freedom of bosons and fermions, so the simplest supersymmetric model may be the minimal extension of the SM, in which each particle in the line is the particle-superpartner. Note also that such a model must contain two doublet of scalar Higgs fields, based

[1]a-gurska@yandex.ru

on the requirements of the chiral fields in the Lagrangian. We receive so-called minimal supersymmetric standard model (MSSM) [14]. It has long been popular, but the problem of uncertainty of the mass parameter (μ) of the Higgs fields remained in it. The solution to this problem is the introduction of the additional Superpole singlet in the Higgs sector. The resulting model is called nonminimal supersymmetric standard model (NMSSM) [15, 16]. Nowadays this model is the most appropriate compared with other developed supersymmetric theories.

2 A local minimum of the Higgs potential

Next, we will use the Higgs field designations adopted in the method of the effective potential. Higgs fields can be parameterized:

$$\Phi_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \\ \phi_1^- \end{pmatrix}, \ \Phi_2 = e^{i\theta} \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}} e^{i\varphi}(v_3 + h_3 + ia_3) \tag{1}$$

where, in the general case, the vacuum values of the Higgs fields are complex.

Also, general view of the renormalized Higgs potential:

$$\begin{aligned} U(\Phi_1, \Phi_2, S) = & - \mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \mu_3^2(S^\dagger S) + \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \\ & + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5^*}{2}(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) + \\ & + \lambda_6(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_1) + \lambda_6^*(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + \lambda_7^*(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ & + k_1(\Phi_1^\dagger\Phi_1)(S^\dagger S) + k_2(\Phi_2^\dagger\Phi_2)(S^\dagger S) + k_3(\Phi_1^\dagger\Phi_2)(S^\dagger S^\dagger) + k_3(\Phi_2^\dagger\Phi_1)(SS) + \\ & + k_4(S^\dagger S)^2 + k_5(\Phi_1^\dagger\Phi_2)S + k_5(\Phi_2^\dagger\Phi_1)S^\dagger + k_6 S^3 + k_6(S^\dagger)^3 \end{aligned}$$

Explicit violation of CP-invariance is possible with complex parameters λ_5, λ_6, λ_7. Also, in NMSSM, there is another possibility, it is a mixing of doublets and singlet of Higgs fields.

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: $\mu_1^2, \mu_2^2, \mu_{12}^2$.

$$\begin{aligned} \mu_1^2 = & \frac{1}{2}\Big(v^2\lambda_1\cos^2\beta + v^2(\lambda_3 + \lambda_4 + Re\lambda_5)\sin\beta^2 + v^2\sin\beta(3Re\lambda_6\cos\beta + Re\lambda_7\tan\beta)\Big) + \\ & + \frac{1}{2}k_1 v_3^2 + (\frac{1}{2}Rek_3 v_3 + \frac{1}{\sqrt{2}}Rek_5)v_3 \ \tan\beta, \\ \mu_2^2 = & \frac{1}{2}\Big(v^2\lambda_2\sin^2\beta + v^2(\lambda_3 + \lambda_4 + Re\lambda_5)\cos\beta^2 + v^2\cos\beta(3Re\lambda_7\sin\beta + Re\lambda_6\cot\beta)\Big) + \\ & + \frac{1}{2}k_2 v_3^2 + (\frac{1}{2}Rek_3 v_3 + \frac{1}{\sqrt{2}}Rek_5)v_3 \ \cot\beta, \end{aligned}$$

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

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

These conditions should be used for finding the physical States of Higgs bosons.

3 The physical States of Higgs bosons

In NMSSM for the neutral Higgs bosons in the basis(h_1, h_2, h_3, A, a_3), $A = -a_1\sin\beta + a_2\cos\beta$ mass matrix has undivided structure. In case with CP violation we should consider the matrix 5×5 for which the eigenvalues do not have a definite CP-parity:

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

where each m_{ij} is determined through the second derivative $\frac{\partial^2 U}{\partial v_i^2}$:

$$m_{11} = \frac{v^2}{2}(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + 2(\lambda_3 + \lambda_4 + Re\lambda_5)\cos^2\beta\sin^2\beta +$$
$$+4Re\lambda_6\cos^3\beta\sin\beta + 4Re\lambda_7\cos\beta\sin^3\beta),$$
$$m_{12} = \frac{1}{4}(3v^2(Im\lambda_5\sin 2\beta + Im\lambda_6(1+\cos 2\beta) + Im\lambda_7(1-\cos 2\beta))$$
$$-2v_3(v_3 Imk_3 + \sqrt{2}Imk_5)),$$
$$m_{13} = \frac{1}{8}v^2(-\lambda_1(\sin 2\beta + \sin 4\beta) + \lambda_2(\sin 2\beta - \sin 4\beta) + 2(\lambda_3 + \lambda_4 + Re\lambda_5)\sin 4\beta +$$
$$+4(Re\lambda_6(\cos 2\beta + \cos 4\beta) + Re\lambda_7(\cos 2\beta - \cos 4\beta)),$$
$$m_{14} = v(v_3(k_1\cos^2\beta + k_2\sin^2\beta) + (v_3 Rek_3 + \frac{1}{\sqrt{2}}Rek_5)\sin 2\beta),$$
$$m_{15} = v(v_3 Imk_3 - \frac{1}{\sqrt{2}}Imk_5)\sin 2\beta,$$
$$m_{22} = -\frac{1}{8}\left(v^2(2Re\lambda_5\sin 2\beta + Re\lambda_6(1+\cos 2\beta) + Re\lambda_7(1-\cos 2\beta)) +\right.$$
$$\left.+\,2v_3(v_3 Rek_3 + \sqrt{2}Rek_5)\right)\csc\beta\sec\beta,$$
$$m_{23} = \frac{1}{2}v^2(Im\lambda_5\cos 2\beta + (Im\lambda_7 - Im\lambda_6)\sin 2\beta),$$
$$m_{24} = -v(v_3 Imk_3 + \frac{1}{\sqrt{2}}Imk_5), \qquad m_{25} = v(v_3 Rek_3 - \frac{1}{\sqrt{2}}Rek_5),$$

$$m_{33} = \frac{1}{16}\left(v^2(\lambda_1(1-\cos 4\beta) + \lambda_2(1-\cos 4\beta) + 2(\lambda_3+\lambda_4+Re\lambda_5)(\cos 4\beta - 1) - \right.$$
$$-(.4(Re\lambda_6(\cot\beta + \sin 4\beta) + Re\lambda_7(\tan\beta - \sin 4\beta))$$

$$\left. -4v_3\left(Rek_3v_3 + \sqrt{2}Rek_5\right)\csc\beta\sec\beta\right),$$
$$m_{34} = \frac{1}{2}v\left(v_3(k_2-k_1)\sin 2\beta + 2\left(v_3Rek_3 + \frac{1}{\sqrt{2}}Rek_5\right)\cos 2\beta\right),$$
$$m_{35} = v\cos 2\beta\left(v_3Imk_3 - \frac{1}{\sqrt{2}}Imk_5\right),$$
$$m_{44} = v_3^2k_4 - \frac{1}{2\sqrt{2}}\left(\frac{v^2}{v_3}Rek_5\sin\beta\cos\beta + 3v_3Rek_6\right),$$
$$m_{45} = v^2Imk_3\sin\beta\cos\beta - 3\sqrt{2}v_3Imk_6,$$
$$m_{55} = -\frac{1}{4v_3}(v^2(4Rek_3v_3 + \sqrt{2}Rek_5)\sin\beta\cos\beta + 9\sqrt{2}v_3^2Rek_6).$$

4 Scenario a light Higgs boson

Some free parameters of the model are enclosed in the range of possible values, but do not have a fixed value:

$$1.0 < tg\beta \leq 60, \quad M_1 = M_2, \quad 100\,\text{GeV} \leq M_2 \leq 2000\,\text{GeV},$$
$$0.0001 \leq \lambda \leq 0.7, \quad 0 \leq \kappa \leq 0.65.$$
$$0\,\text{GeV} \leq A_\lambda \leq 1000\,\text{GeV}, \quad -100\,\text{GeV} \leq A_\kappa \leq -10\,\text{GeV}$$

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

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

We collect the parameters into sets that satisfy the conditions of local minimum of the Higgs potential, we can build some scenarios that are implemented in NMSSM for different masses of the Higgs bosons. We also examined possible scenarios in the case of CP conservation for comparison. We also correlated our results with the mass of the lightest particle of the dark matter neutralino $m_{\chi_1^0}$. In cases 1 and 2 we use the notation m_{h_i} for neutral CP-even and m_{a_i} for neutral CP-odd physical states Higgs bosons. In cases 3 and 4, m_{H_i} means states with undefined parity. So, we can choose the parameters so that you will get similar mass of neutral Higgs bosons, or there are similar masses to one CP-even and second CP-odd Higgs bosons.

Parameters of model \	CP invariance 1	2	CP violation 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

The fourth scenario is particularly interesting, since we have the mass value for the Higgs boson is below the experimentally allowed value. We assume the existence of such particles, and it can not be found on experiment that has a certain CP parity. It should be noted that CP violation we consider as one of the causes of the baryon asymmetry. It is believed that this occurred at an early stage of the formation of the Universe, in the process of biogenesis. In the version of the electroweak baryogenesis are the requirements on the mass of the Higgs boson, which value must be less than 50 GeV [17].

5 Summary and Outlook

We have considered the method of finding the local minimum of the Higgs potential in NMSSM with the violation of CP invariance. Also, we found the physical condition of the Higgs bosons. We considered possible scenarios, which satisfy the possible values of the free parameters of the model. The light Higgs scenario with undefined CP parity of the most interesting, as it may solve the problem of the electroweak baryogenesis.

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