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Critical temperatures in extensions of Higgs sector

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Abstract. In this paper the control parameters of the Higgs potential are considered in the framework of supersymmetric models MSSM and Next-to-MSSM. The determination of these parameters is an important part related to the explanation of the CP violation evidence and electroweak phase transition evolution from the energy of the supersymmetry scale to the standard model energy scale. There is a discussion here on the problem of violation of CP invariance and its effect on the Higgs potential control parameters determination and the dark matter experimental constraints. Also the problem of determining the Potential $\leftrightarrow$ Free Energy parameters from the points of temperature field theory and critical temperatures view is considered.

1 Introduction

Inconsistency of conditions for the first-order phase transition in the SM and experimental data on the Higgs boson mass provided by LHC initiates the beyond standard model analyses where the case of MSSM and NMSSM were investigated in the first place [1, 2]. Simultaneously three main criteria should be ensured by the admissible scenarios (1) strongly first order phase transition, v_C/T_C >1, for electroweak baryogenesis (2) sufficiently heavy CP-even Higgs boson, consistent with collider exclusions (3) dark matter candidate.

Preliminary analysis of the zero and nonzero finite-temperature MSSM and NMSSM effective potentials has been performed [3–5] in the various scenarios. In comparison with other analyses not only the case of noninteracting cosmic plasma in the background fields (zeroth approximation in the couplings or the "one-loop" approximation for the free energy at nonzero temperature) has been considered [5]. "Genuine one-loop" MSSM and NMSSM diagrams with the Higgs bosons interacting with the third generation of scalar quarks and gluinos were evaluated (socalled "threshold corrections" to the boundary condition for the two-doublet potential in terms of control parameters $\lambda_1 = \lambda_2 = (g_1^2 + g_2^2)/8$, $\lambda_3 = (g_2^2 - g_1^2)/4$, etc. at the scale M_{SUSY}). General case of the soft SUSY breaking terms was considered and results for the one-loop finite-temperature corrections have been obtained in the full parameter space m_{Q_i}, m_{U_i}, m_{D_i}, A, μ, M_{SUSY}, tgβ, $m_{H^\pm}$, v_3. In the case of two background fields v_1 and v_2 one can find the two-dimensional surface of stationary points (the surface of extrema) where some configuration of the Higgs fields can be defined in any point of the surface. The

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shape of the surface of stationary points and the shape of the field configurations surface are parametrically sensitive. For example, the phase transition is possible when the "flat direction" in (v_1, v_2) plane can formed by the surface of stationary points. Flat directions can appear in a limited regions of the MSSM parameter space. The surface of field configurations must ensure positively defined squared masses of Higgs bosons. For example, "saddle configurations" (corresponding to 'tachyonic' objects) are excluded in this case. Some examples of the effective potential surface for stationary points and the regions of positively defined CP-even Higgs boson masses can be found in [6].

One of the most popular models in particle physics today is the minimal and next-to-minimal supersymmetry (NMSSM) models [4, 7]. Its consequences have long been checked on the LHC. The number of free parameters of the model makes it possible to build different research scenarios. However, a separate task is to consider the extended Higgs sector and solve a number of problems related to the stability of the vacuum, the explanation of baryon asymmetry in agreement, for example, with the hypothesis of electroweak baryogenesis [1, 8]. Here, the focus is on the Higgs potential and parameters, which, to date, do not have a precise definition, but are important, because they arise further in the calculation of the masses of the Higgs bosons, and also other physical parameters of the model.

2 On the phase transition

In the works of the authors [9, 10], the potential of the NMSSM Higgs and the system of fields are considered as:

$$\Phi_1 = \begin{pmatrix} \phi_1^- \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + i\chi_1) \end{pmatrix}, \quad \Phi_2 = e^{i\theta}\begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + i\chi_2) \end{pmatrix}, \qquad (1)$$

$$S = \frac{1}{\sqrt{2}} e^{i\varphi}(v_3 + \phi_3^0 + i\chi_3)$$

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

The parameters $\lambda_5, \lambda_6, \lambda_7$ are zero on the supersymmetry scale. Also, some of the parameters κ range near zero. But at the scale of the standard model energy these parameters are not zero. The calculation of the corrections to these parameters may give an opportunity to answer the question of how these parameters are defined and what these values may be.

In general, the doublets of the Higgs potential contain the phases θ, φ of spontaneous CP-violation . The need to introduce such phases is related to the problem of baryon asymmetry [11] and an attempt to explain it within the framework of supersymmetry by including additional sources of CP-violation in the Higgs sector. At the same time, violations of this symmetry can be implemented explicitly. This was described in detail in the previous work of the authors [12]. The introduction of CP-violation may affect the determination of the values of the control parameters of the potential.

It is necessary to satisfy the conditions of local minimum existing for getting of the Higgs bosons physical states in potential U in the space of vacuum expectation values v_1, v_2, v_3. We should calculate extrema conditions: $\frac{\partial U}{\partial v_1} = 0$, $\frac{\partial U}{\partial v_2} = 0$, $\frac{\partial U}{\partial v_3} = 0$, and based on its we can determine and fix some combinations of parameters $\mu_1^2, \mu_2^2, \mu_{12}^2$ as:

$$\begin{aligned}\mu_1^2 = \frac{1}{v_1}(&Imk_3 v_2 v_3^2 \cos(\theta - 2\varphi) - Im\lambda_5 v_1 v_2^2 \sin(2\theta) - Imk_5 v_2 v_3 \sin(\theta + \varphi) - \\ &v_2 \cos\theta\left(3Im\lambda_6 v_1^2 + Im\lambda_7 v_2^2\right) + k_1 v_1 v_3^2 - Rek_3 v_2 v_3^2 \sin(\theta - 2\varphi) - \\ &Re\lambda_5 v_1 v_2^2 \cos(2\theta) - Rek_5 v_2 v_3 \cos(\theta + \varphi) + 3Re\lambda_6 v_1^2 v_2 \sin\theta + Re\lambda_7 v_2^3 \sin\theta + \\ &\lambda_3 v_1 v_2^2 + \lambda_4 v_1 v_2^2 + \lambda_1 v_1^3)\end{aligned}$$

$$\begin{aligned}\mu_2^2 = \frac{1}{v_2}(&Imk_3 v_1 v_3^2 \cos(\theta - 2\varphi) - Im\lambda_5 v_1^2 v_2 \sin(2\theta) - Imk_5 v_1 v_3 \sin(\theta + \varphi) - \\ &v_1 \cos\theta\left(Im\lambda_6 v_1^2 + 3Im\lambda_7 v_2^2\right) + k_2 v_2 v_3^2 - Rek_3 v_1 v_3^2 \sin(\theta - 2\varphi) - \\ &Re\lambda_5 v_1^2 v_2 \cos(2\theta) - Rek_5 v_1 v_3 \cos(\theta + \varphi) + Re\lambda_6 \mathrm{v}1^3 \sin(\theta) + \\ &3Re\lambda_7 v_1 v_2^2 \sin\theta + \lambda_3 v_1^2 v_2 + \lambda_4 v_1^2 v_2 + \lambda_2 v_2^3)\end{aligned}$$

$$\begin{aligned}\mu_3^2 = \frac{1}{v_3}(&2Imk_3 v_1 v_2 v_3 \cos(\theta - 2\varphi) - Imk_5 v_1 v_2 \sin(\theta + \varphi) + 3Imk_6 v_3^2 \cos(3\varphi) + \\ &k_1 v_1^2 v_3 + k_2 v_2^2 v_3 + 2k_4 v_3^3 - 2Rek_3 v_1 v_2 v_3 \sin(\theta - 2\varphi) - \\ &Rek_5 v_1 v_2 \cos(\theta + \varphi) - 3Rek_6 v_3^2 \sin(3\varphi))\end{aligned}$$

The local minimum conditions are expressed in terms of the spontaneous CP-violation phases in the general case.

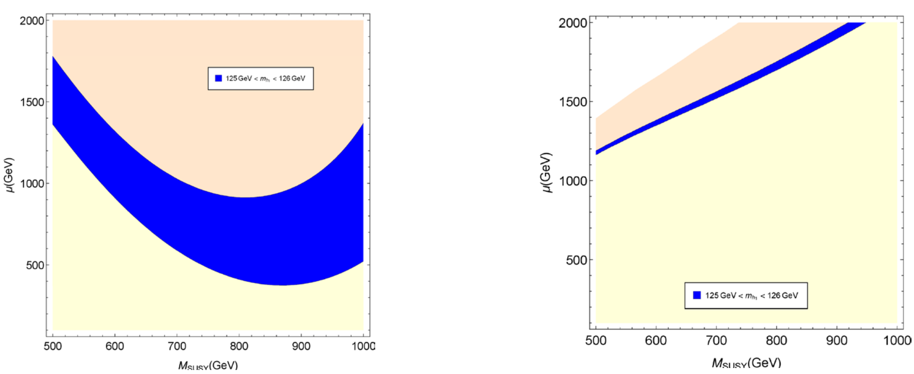
Another interesting problem is related to the consideration of the phase transition in the framework of the temperature field theory, so that the control parameters can be functions of the temperature.

In conference report authors discuss features of some topological methods for baryogenesis and phase transition analysis, including models with an extended scalar sectors at finite temperatures. The first and second differential forms can be implemented for the effective potential. The classic picture of baryogenesis in grand unification theories has changed significantly with the standard model development and the phase diagram of electroweak interactions is specificated with experimental data on Higgs boson physics. Currently the minimal extension of the scalar sector has a less likely to be realized, therefore, an important role is played by researching of the non-minimal extensions. In previous papers authors considered a general scalar Higgs sector, including the violation of CP-invariance and temperature corrections for control parameters, conditions for the effective potential that lead to the phase transition of the strong first order required for the generation of the observed baryon asymmetry. Additional chiral field plays here the role of the phase transition stabilizing foam. The feature of the upcoming research is that the violations of symmetries and temperature contributions of the self-potential affect the dark sector is supersymmetric models, which could have consequences for cosmology.

In addition to the direct searches for dark matter, there are other factors that lead to restrictions on the parameters of NMSSM. For example, in article [13] the possibility of detecting the singlet Higgs boson from two-photon decay is considered. That is possibility to significantly change the mass of the cold dark matter particles and intensity of their interaction with other particles and the ability to participate in electroweak decays, including the decay of Higgs bosons. Results for Higgs fields in the case of CP-violating and temperature corrections are used for the dark sector physical parameters calculations. Also, the annihilation of neutralinos in the framework of quantum field theory in conjunction with Feynman diagram approach was taking into account with one-loop corrections. Temperature one-loop effective potential for NMSSM is reconstructed. Physical masses conditions is determined and the one-loop corrections to the dimensionless parameters of the effective potential are evaluated in the framework of NMSSM. The general case is investigated for calculations of one-loop diagrams with different masses in finite temperature field theory, some representations of infinite series and generalized function of Hurwitz are proposed. Surfaces of the stationary points in space background fields and matrix stability are reconstructed, including difference from SM physical basis in the alignment limit. Scenarios of stationary points and critical temperatures were determined, extreme curves and surfaces based on the definition of Grobner bases are also considered.

3 Restrictions on the parameters of the MSSM

Using the experimental value of Higgs mass we searched the region of MSSM parameter space, where the signal can be interpreted as one of neutral CP-even MSSM Higgs bosons. We changed two parameters, which are coordinates at plane, other parameters were fixed.



a) $\tan\beta = 5$

b) $\tan\beta = 50$

Figure 1. Contour plot in $\mu - M_{SUSY}$ plane. Selected region: 125 GeV $<m_{h_1}<$126 GeV (blue region). Fixed parameters: $A_{t,b}$ = 1000 GeV, $m_{H^\pm}$ = 300 GeV, $\varphi = \dfrac{\pi}{3}$.

Contour plots at μ - M_{SUSY} plane are presented in figure 1. The physical state of the Higgs boson is possible for any value of M_{SUSY}, when $\tan\beta = 5$. The required area narrows as the value of $\tan\beta$ increases to 50.

Contour plot at $\varphi - \tan\beta$ plane is presented in figure 2. The parameter φ can take any values, and $\tan\beta$ can take only small or large values.

Contour plot at $\varphi - \tan\beta$ plane is presented in figure 3. Required region exist for small values of $\tan\beta$, when temperature $T = 500$ GeV.

Contour plots at $m_A - \tan\beta$ plane are presented in figure 4. Physical state of Higgs boson with the mass 125 GeV $< m_{h_1}$ <126 GeV exict for any values of m_A. The values of $\tan\beta$ decreases, when T increases up to 500 GeV.

In NMSSM due to the redefinition of the parameter μ, we can just take into account the mass of light matter, because when calculating the mass of neutral Higgs boson in MSSM μ parameter exist also. For MSSM values from the contourplot the masses will be greater.

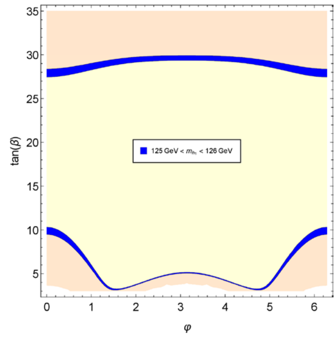


Figure 2. Contour plot in $\varphi - \tan\beta$ plane. Selected region: 125 GeV $< m_{h_1} <$126 GeV (blue region). Fixed parameters: μ = 2000 GeV, $A_{t,b}$ = 1000 GeV, M_{SUSY} = 500 GeV, $m_{H^\pm}$ = 300 GeV.

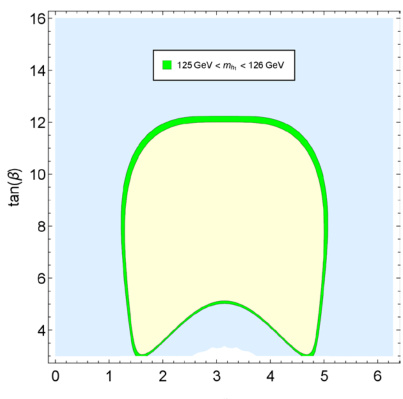
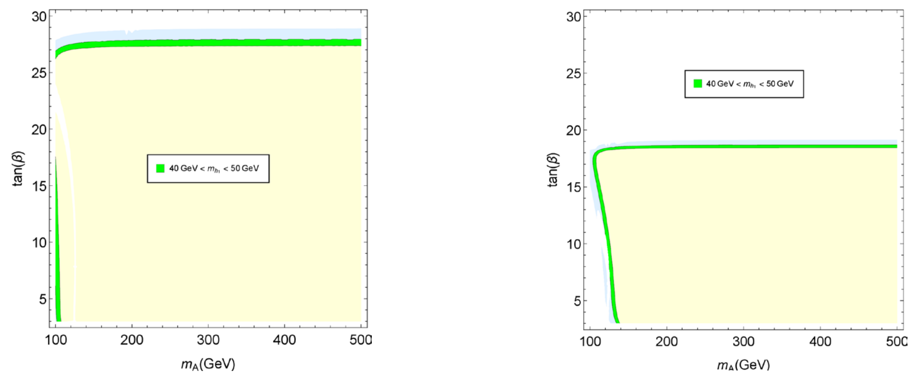


Figure 3. Contour plot in $\varphi - \tan\beta$ plane. Selected region: 125 GeV $< m_{h_1} <$126 GeV (green region). Fixed parameters: μ = 2000 GeV, $A_{t,b}$ = 1000 GeV,m_Q=500 GeV, m_t=800 GeV, m_b=200 GeV,$m_{H^\pm}$ = 300 GeV,T = 500 GeV.

For the requirements of the strong phase transition of the first order in the existence of electroweak baryogenesis, or rather, it is need to limit the mass of the lightest Higgs boson. Why can't consider the phase transition be of second order. The baryon asymmetry generated during the electroweak phase transition disappears over time. There the thermodynamic equilibrium comes and the third condition of Sakharov is not fulfilled. The thermodynamic equilibrium must be significantly disturbed, which is possible only at the first-order phase transition. The model of cosmological bubbles of the scalar field is used in the description of the phase transition of the first order. In almost all models, baryon asymmetry occurs near the wall of such a bubble. An additional singlet of a complex scalar field with a non-zero vacuum value plays an important role in the implementation of the phase transition scenario in the NMSSM. Elucidation of the nature of the phase transition and calculation of the critical temperature corresponding to it are important tasks of theoretical cosmology.



a)$T = 10GeV$ b)$T = 500GeV$

Figure 4. Contour plot in $m_A - \tan\beta$ plane. Selected region: 125 GeV $< m_{h_1} <$ 126 GeV (green region). Fixed parameters: $\mu = 2000$ GeV, $A_{t,b} = 1000$ GeV,m_Q=500 GeV, m_t=800 GeV, m_b=200 GeV,$m_{H^\pm} =$ 300 GeV.

4 Restrictions on the parameters from the dark matter data

To date, the direct search for dark matter give some restrictions on the mass of the candidate for the dark matter role. This particle is neutral in the NMSSM. Note that there may also be a hypothetical axion particle, however, its existence in the model is determined by the type of the Higgs potential. In our case $\sim \kappa S^3$-component excludes the axion.

There are significant restrictions on the particle mass in the accelerator experiments: 1 GeV [14]. According to the registration of possible annihilation of dark matter, there are more relaxed restrictions on the mass: for the following channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, gg, $u\bar{u}$ and b^+b^- there are according mass values: 40 GeV, 28 GeV, 30 GeV, 57 GeV, 58 GeV and 66 GeV [15].

A separate task is to consider the range of possible values of potential parameters in agreement with the neutral masses. It should be said that the choice of potential parameters is limited not only by the dark matter masses, but also by the values of the Higgs boson masses, where, as mentioned above, one of the particles should correspond to the observed boson.

We can determine the ranges of possible values of the basic dimensionless parameters of the NMSSM as follows[16]:

$$\kappa \to 0: \ \lambda = 0,41 \div 0,7 \tag{2}$$

$$\lambda \to 0: \ \kappa = 0,5 \div 0,65 \tag{3}$$

The value of the vacuum parameter is fixed $\upsilon_3 = 300$ GeV. In general, this parameter requires attention, because its value is dictated by the features of mixing between doublets of Higgs fields. Because of what, there are still restrictions on the choice of the value of υ_3, but at least it is not a zero parameter.

The relationship of the symbols notations in the general NMSSM parameters with our symbols is as follows:

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

5 Conclusion

The problem of control parameters evolution evaluation for the effective Higgs potential has been analysed. Main contributions of the MSSM and NMSSM to the control parameters have been evaluated in the finite-temperature theory with the following investigation of the effective NMSSM potential at the stationary points. In the framework of NMSSM the one-loop corrections to the parameters of effective Higgs potential with two doublets and chiral singlet at finite temperature were calculated. The scalar quarks mass splitting influences strongly on the effective parameters of temperature potential, providing interesting possibilities for the phase transition evidence. The physical masses vanish, when the temperature increases up to the critical values, which corresponds to the phase transition. In the limiting case, when the temperature is equal to zero and all mass parameters of the soft SUSY breaking sector are degenerated, the predictions for observables from two-doublet potential coincide with known previous results.

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References

[1] de Vries, J., Postma, M., van de Vis, J., Graham White. J. High Energ. Phys. (2018) 2018: 89.

[2] M. Reichert, A. Eichhorn, H. Gies, J. M. Pawlowski, T. Plehn, and M. M. Scherer Phys. Rev. D 97, 075008

[3] Ellwanger U., Rodríguez-Vázquez M. J. High Energ. Phys. (2016) 2016: 96.

[4] C.Beskidt, W. de Boer, D.I.Kazakov, Physics Letters B Volume 782, Pages 69–76.

[5] M. Dolgopolov, M. Dubinin, E. Rykova, J. Mod. Phys. 2 (2011) 301; Phys.Atom.Nucl. 73 (2010) 1032; Phys.Atom.Nucl. 72 (2009) 167.

[6] Dolgopolov M. V., Dubinin M. N., Rykova E. N. Two-Higgs doublet potential of the MSSM at finite temperature and Higgs boson masses // Quarks 2008. N V. 1. P. 1-7.

[7] M.Maniatis, IJMP A., V.25, 3505–2602 (2010).

[8] Demidov, S.V., Gorbunov, D.S., Kirpichnikov, D.V. J. High Energ. Phys. (2016) 2016: 148. High Energ. Phys. (2017) 2017: 80.

[9] T. V. Volkova, M. V. Dolgopolov, M. N. Dubinin, and E. N. Rykova, Vestn. os. Tekh. Univ., Ser. Fiz.-Mat. Nauki 2 (31), 233–242 (2013).

[10] Gurskaya A.V., Dolgopolov M.V., Rykova E.N. Physics of Particles and Nuclei 2017. Vol. 48. Issue 5. P. 822-826.

[11] A. D. Sakharov, JETP Lett. **5**, 24 (1967).

[12] Gurskaya A.V., Dolgopolov M.V., EPJ Web of Conferences, V.125, 02011 (2016)

[13] Yang, KC. J. High Energ. Phys. (2018) 2018: 99.

[14] Mendez M.del R.A. et al., Journal of Physics:Conference Series, V.468, 012006 (2013)

[15] Chan, M.H. Astrophys Space Sci (2017) 362: 147.

[16] Gurskaya A.V., Dolgopolov M.V., EPJ Web of Conferences, V.158, 02010 (2017)