ELECTROWEAK PHASE TRANSITION WITH MAGNETIZATION IN THE SCALAR SECTOR OF THE 2HDM

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We discuss theoretical and phenomenological aspects of the two-Higgs-doublet extensions of the Standard model. In modern notation the h2HDM is the model with $m_h = 125.26$ GeV, where the lightest neutral scalar particle in 2HDM is the usual Higgs boson in Standard Model.

The parametric space of this model is very rich and admits many scenarios of New Physics' phenomenology.The many restrictions and conditions should be satisfied. One of them is the Sakharov's conditions for the formation of the baryon asymmetry of the Universe in models with extra scalar fields. We try to show that we can satisfy them in the h2HDM and find the region of parametric space where the electroweak phase transition is first order. The Sakharov's conditions are not satisfied in Standard Model but it is fundamental problem of modeling the Universe, so the searching of New physics this way is relevant.

Keywords: EWPT, 2HDM, symmetries, Lie groups, non-Abelian interactions

Received 08.09.2024; Received in revised form 09.10.2024; Accepted 15.11.2024

1. Introduction

The Standard model explains the physics of high energy particles extremely good. It satisfies a lot of modern experimental data. The physics beyond Standard model is one of the modern steps of understanding the nature. One of unsolved problems of Standard model is baryogenesis. In this theory with mass of Higgs boson more 75 GeV the Sakharov conditions [1] are violated.

There are many reasons to think that the Two Higgs doublet model is a good extension of Standard model with the extra doublet of scalar fields. In the present paper, we show the way of simulations and finding the parametric space of the 2HDM where we can satisfy the Sakharov's conditions. We use a high temperature effective potential for the scalar sector of the model with spontaneous generation of magnetic fields [4, 5]. We are interested in the role of magnetic fields in evolution of early Univers and in processes near critical temperature for EWPT.

2. Effective potential of 2HDM

We consider a general CP-conserving 2HDM with a softly broken Z_2 symmetry, described by the following potential [2]:

$$\begin{aligned} V_{Higgs} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \\ &+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \\ &+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left(\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right), \end{aligned} \quad (1)$$

where the term proportional to m_{12}^2 breaks the Z_2 symmetry. Φ_1 and Φ_2 are the pair of doublets of the scalar fields:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}, \quad (2)$$

with the vacuum expectation values $v_{1,2}$ and $v^{SM} = \sqrt{v_1^2 + v_2^2} = 246.22$ GeV.

$$< \Phi_1 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, < \Phi_2 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \tag{3}$$

We calculate parameters m_{11} and m_{22} from equations for stability of vacuum:

$$\begin{aligned} 0 &= \frac{\partial V_{Higgs}}{\partial \Phi_1} = 2m_{11}^2 v_1 - 2m_{12}^2 v_2 + \lambda_1 v_1^3 + \lambda_3 v_2^2 v_1 + \lambda_4 v_1 v_2^2 + \lambda_5 v_1 v_2^2 \\ 0 &= \frac{\partial V_{Higgs}}{\partial \Phi_2} = 2m_{22}^2 v_2 - 2m_{12}^2 v_1 + \lambda_2 v_2^3 + \lambda_3 v_1^2 v_2 + \lambda_4 v_1^2 v_2 + \lambda_5 v_1^2 v_2 \end{aligned} \tag{4}$$

We use usual notation for the mixing angles:

$$tan\beta = \frac{v_2}{v_1}, \quad tan2\alpha = \frac{2(-m_{12}^2 + v_1 v_2(\lambda_3 + \lambda_4 + \lambda_5))}{m_{12}^2(v_2/v_1 - v_1/v_2) + \lambda_1 v_1^2 - \lambda_2 v_2^2}. \tag{5}$$

And as a result we can write masses of scalar particles:

$$\begin{aligned} m_h^2 &= M^2 cos^2(\alpha - \beta) + v^2 \left(\lambda_1 sin^2\alpha cos^2\beta + \lambda_2 cos^2\alpha sin^2\beta - \frac{\lambda_3 + \lambda_4 + \lambda_5}{2} sin2\alpha sin2\beta \right); \\ m_H^2 &= M^2 sin^2(\alpha - \beta) + v^2 \left(\lambda_1 cos^2\alpha cos^2\beta + \lambda_2 sin^2\alpha sin^2\beta + \frac{\lambda_3 + \lambda_4 + \lambda_5}{2} sin2\alpha sin2\beta \right); \\ m_A^2 &= M^2 - \lambda_5 v^2; \\ m_{H^\pm}^2 &= M^2 - \frac{\lambda_4 + \lambda_5}{2} v^2, \end{aligned} \tag{6}$$

where $M^2 = m_{12}^2/(sin\beta cos\beta)$ and $v^2 = v_1^2 + v_2^2$.

To include finite temperature part and interaction with magnetic fields to full potential we should add one loop part [3]. For one charged scalar degree of freedom with mass m and charge e we have general expression:

$$V = -\frac{1}{16\pi^2} \sum_{-\infty}^{\infty} \int_0^{\infty} \frac{ds}{s^3} e^{-(m^2 s + n^2/4sT^2)} \frac{eHs}{sh(eHs)}, \tag{7}$$

where H - magnetic fields strength and T- temperature.

For our calculations we present the next notions:

1) For charged scalar degree of freedom:

$$\begin{aligned} V^{Charged}(m, H, T) &= V_0^{Charged}(m, H) + V_T^{Charged}(m, T, H), \\ V_0^{Charged}(m, H) &= -\frac{1}{16\pi^2} \int_0^{\infty} \frac{ds}{s^3} e^{-m^2 s} \frac{eHs}{sh(eHs)}, \\ V_T^{Charged}(m, T, H) &= -\frac{1}{8\pi^2} \sum_{n=1}^{\infty} \int_0^{\infty} \frac{ds}{s^3} e^{-(m^2 s + n^2/4sT^2)} \frac{eHs}{sh(eHs)} \end{aligned} \tag{8}$$

2) For neutral scalar degree of freedom:

$$V^{Neutral}(m,T) = V_0^{Neutral}(m) + V_T^{Neutral}(m,T),$$
$$V_0^{Neutral}(m) = -\frac{1}{16\pi^2}\int_0^\infty \frac{ds}{s^3}e^{-m^2 s},$$
$$V_T^{Neutral}(m,T) = -\frac{1}{8\pi^2}\sum_{n=1}^{\infty}\int_0^\infty \frac{ds}{s^3}e^{-(m^2 s+n^2/4sT^2)}. \tag{9}$$

For temperature part we have the next physical conditions:

$$V^{Charged}(m,H=0,T) = V^{Neutral}(m,T)$$
$$V_T^{Charged}(m,H,T=0) = V_T^{Neutral}(m,T=0) = 0 \tag{10}$$

To use formulas above we make Mellin's transformations and use definition of K-function (11) to find high temperature asymptotic(see Appendix A) and for $n=0$ we have one loop contribution, which should be renormalized with adding counter terms to final potential.

$$\int_0^\infty dx x^{n-1}\,\mathsf{exp}\left(-ax-\frac{b}{x}\right) = 2\left(\frac{b}{a}\right)^{n/2} K_n(2\sqrt{ab}) \tag{11}$$

To make research about electroweak transition we use full potential as function of temperature, magnetic fields and the vacuum expectation values. The potential (1) we write in terms of free parameters - λ_i, v_1, v_2 and m_{12}. We are interested in behavior of potential as dependence on increasing the temperature.

As a results we have the following expression:

$$V(T,H,v_1,v_2) = \frac{H^2}{2} + V_{Higss}(v_1,v_2) + \sum_{A,h,H} V_T^{Neutral}(m,T) + \sum_{H^\pm} V_{HT}^{Charged}(m,H,T) +$$
$$+\sum_{particles} V_{CT}(v1,v2,T,H), \tag{12}$$

where $V_{CT}(v1,v2,T,H)$ is the corresponding counter terms.The location of the minimum is the same as for the tree level potential. The tree level masses are preserved at $H=0$ and $T=0$.

For calculations we use the following conditions:

$$\left.\frac{\partial V}{\partial H^2}\right|_{H=0,T=0,\phi_i=v_i} = \frac{1}{2};$$
$$\left.\frac{\partial V}{\partial \phi_i}\right|_{H=0,T=0,\phi_i=v_i} = 0;$$
$$\left.\frac{\partial^2 V}{\partial \phi_i \partial \phi_j}\right|_{H=0,T=0,\phi_i=v_i} = \left.\frac{\partial^2 V_{Higgs}}{\partial \phi_i \partial \phi_j}\right|_{H=0,T=0,\phi_i=v_i}. \quad (13)$$

This potential we should use to find parameters where the Sakharov's conditions are satisfied.

3. Simulations

In this chapter we want to explain the algorithm of generation of the parameters and show the main results clearly. For numerical simulations, we need to fix the values of λ_i and m_{11}, m_{12}, m_{22} parameters. If we have these parameters we can calculate the masses of particles. As a result, we find V as the function of v_1, v_2, T and H for EWPT. What is the correct way to fix all the parameters of the model? We provide the next way.

In our simulation, we randomly generate λ_1–λ_5, using condition for unitarity and stability (e.g. [6]), and the value of $tan\beta < 100$. For each combination of $\{\lambda_i, tan\beta\}$ we numerically solve the equations (2) and (3) with $v^{SM} = \sqrt{v_1^2 + v_2^2} = 246.22$ GeV and $m_h = 125$ GeV. As a result, we have the values m_{12} and α. The next step is to calculate m_{11} and m_{22} using formulas (4). After the following steps we obtain the point in the parametric space for h2HDM - $\{\lambda_i, m_{11}, m_{12}, m_{22}, \alpha, tan\beta\}$. For the next calculations we omit the points with $m_{12}^2 > 10$ because we are interested in a soft Z_2-symmetry violation.

Note, the point in the parametric space satisfies the next conditions. For the modern experimental vacuum expectation value we have the model with the modern value of m_h. If we want to see the behavior of this model near the EWPT critical temperature, we need to make the parameters v_1 and v_2 free and independent. At high temperature they should approach to zero in order to minimize the potential, and the $SU(2) \times U(1)$ symmetry should be restored and the particles massless.

4. Discussion

The behavior of the EWPT with magnetic fields is discussed. The role of magnetic fields in satisfying the Sakharov's conditions in the h2HDM is remained open question. The algorithms for simulation points in the parametric space are obtained. The main point for research in this way is finding the parameter space regions of different CP-conserving 2HDMs which are not excluded by experiment. Which has a strongly first order electroweak phase transition with magnetic field as one of parameters. If the points with the first-order phase transition will be found, they are hence the candidate models for explaining the observed matter-antimatter asymmetry of our Universe. This search has been performed by studying the minimum of the potential of the theory as the function of temperature and magnetic field strengths, for many different parameters of the models. We conclude that in the scenario where the Higgs boson which has been found at the LHC is the lightest Higgs particle in the 2HDM can be the models with a strongly first order electroweak phase transition.

Acknowledgements

The author would thank V. Skalozub and D. Becirevic for helpful discussions. This work is partially supported by the ICTP through AF-06/21-01.

5. Appendix A

In this appendix we show the exact calculation of Mellin's transformations for sums of K-function in finite temperature part of potential.

$$V_T^{Neutral}(m,T) = -\frac{1}{8\pi^2}\sum_{n=1}^{\infty}\int_0^{\infty}\frac{ds}{s^3}e^{-(m^2 s+n^2\beta^2/4s)} = -\frac{1}{\pi^2}m^2T^2\sum_{n=1}^{\infty}\frac{K_2(mn/T)}{n^2} \quad (14)$$

$$V_T^{Charged}(m,T,H) = -\frac{1}{8\pi^2}\sum_{n=1}^{\infty}\int_0^{\infty}\frac{ds}{s^3}e^{-(m^2 s+n^2/4sT^2)}\frac{eHs}{sh(eHs)} = -\frac{1}{\pi^2}m^2T^2\sum_{n=1}^{\infty}\frac{K_2(mn/T)}{n^2}+$$
$$+\frac{1}{8\pi^2}\frac{(eH)^2}{3}\sum_{n=1}^{\infty}K_0(mn\beta) - \frac{1}{16\pi^2}\frac{7(eH)^4}{360}\frac{1}{m^4}\sum_{n=1}^{\infty}(m\beta)^2n^2K_2(mn\beta) \quad (15)$$

$$\sum_{n=1}^{\infty}\frac{K_2(n\omega)}{n^2} = \frac{\pi^4}{45\omega^2} - \frac{\pi^2}{12} + \frac{\pi\omega}{6} - \frac{\omega^2}{16}(\frac{3}{4} - \gamma + Log(\frac{4\pi}{\omega})) + \sum_{k=1}^{\infty}\frac{\omega^{2k}\zeta'(2-2k)}{2^{2k}(k-1)!(k+1)!} \quad (16)$$

$$\sum_{n=1}^{\infty}K_0(n\omega) = \frac{\pi}{2\omega} + \frac{\gamma - Log(\frac{4\pi}{\omega})}{2} + \sum_{n=1}^{\infty}\frac{\omega^{2n}\zeta'(-2n)}{2^{2n}(n!)^2} \quad (17)$$

$$\sum_{n=1}^{\infty}(\omega n)^2K_2(n\omega) = \frac{3\pi}{2\omega} - 1 + \frac{1}{8}\omega^4\zeta'(-4) \quad (18)$$

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