DECAY OF THE HIGGS BOSON $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\pi^+\bar{\nu}_\tau$ FOR A NON-HERMITIAN YUKAWA INTERACTION*

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The differential rate of the decay of the Higgs boson (h) to a pair of τ leptons with their subsequent decay in the $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\bar{\nu}_\tau$ channels is studied. The Yukawa interaction between the Higgs boson and the τ leptons is assumed to include scalar (S) and pseudoscalar (PS) couplings. Angular distributions of the pions in the $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$ decay are considered. For real values of the S and PS couplings, this decay is known to be a source of information on $\mathcal{CP}$ violation in the $h\tau\tau$ interaction. In the present paper, the main attention is paid to a possible non-Hermiticity of this interaction. Influence of non-Hermiticity on the distribution of the angle between planes of the $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\bar{\nu}_\tau$ decays, and distribution of the polar angle of one of the pions are analyzed. Asymmetries sensitive to parameters of $\mathcal{CP}$ violation and non-Hermiticity of $h\tau\tau$ interaction are proposed.

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1. Introduction

In the framework of the Standard Model (SM), the fermion masses are generated by the Yukawa interaction between the Higgs field and fermion fields. A measurement of the corresponding couplings is needed for identification of the particle h with the Higgs boson. In the SM, the Higgs boson is the $\mathcal{CP}$-even scalar particle. However, there exist many models with a more complicated structure of the Higgs sector in which both the $\mathcal{CP}$-even and $\mathcal{CP}$-odd scalar particles can exist, as well as particles which do not have definite $\mathcal{CP}$ parity (see recent review [1] and references therein). Therefore, it is possible that the observed Higgs boson h [2, 3] is a mixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd states, although other possibilities are not excluded. Thus,

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clarification of the $\mathcal{CP}$ properties of the Higgs boson is a necessary step in investigation of the mechanism which breaks electroweak symmetry and generates the particle masses. The present status of the LHC measurements of the $\mathcal{CP}$ properties of the Higgs-boson interactions with vector bosons and fermions is reviewed in Ref. [4].

In the SM, the source of violation of the $\mathcal{CP}$ symmetry is an unremovable phase in the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix [5, 6]. Moreover, the existing data indicate that this phase is the dominant source of $\mathcal{CP}$ violation in the flavor-changing processes. However, model calculations show that $\mathcal{CP}$ violation in the SM is too small to explain the matter–antimatter asymmetry in the Universe [7, 8]. There should be other sources of $\mathcal{CP}$ violation beyond the CKM mechanism. Thus, the search for new sources of $\mathcal{CP}$ violation is one of the main directions in the particle physics. One of possibilities in this search is the Higgs boson decay $h \to \tau^-\tau^+$.

The study of the $\mathcal{CP}$ properties and violation of the $\mathcal{CP}$ symmetry in the Higgs sector, using the correlations between the spins of τ leptons created in the Higgs-boson decay, has been carried out in a series of papers, *e.g.* [9–31].

Another important aspect of the Yukawa interaction is Hermiticity of the Lagrangian. In the SM, the Lagrangian of the interaction between fermions and scalar fields satisfies the symmetry with respect to the gauge transformations $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{SU}(3)_c$ and, in addition, it is Hermitian. The latter requirement is imposed on the Lagrangian. In contrast to other terms in the Lagrangian which are naturally Hermitian, the Yukawa interaction "acquires" Hermiticity which may not be necessary. This aspect has been raised in [26].

Note that Ref. [26] also suggested a modification of the SM electroweak interaction to the case of a non-Hermitian interaction between the Higgs fields and fermions. The consideration there was restricted to one generation of the fermions. It was shown that for positive values of the Yukawa couplings, the fermions get the positive mass and the interaction between the Higgs boson and fermions violates $\mathcal{CP}$ symmetry without additional Higgs fields. It seems therefore important to investigate further this mechanism in the Higgs-boson decays.

Let us mention that various aspects of non-Hermitian field theories have been studied in Refs. [32–50]. Influence of non-Hermiticity of the Yukawa interaction on the photon polarization parameters in the $h \to \gamma\gamma$ and $h \to \gamma Z$ decays has been addressed in [51, 52], and on the forward–backward lepton asymmetry in the $h \to \gamma \ell^+ \ell^-$ ($\ell = e, \mu, \tau$) decays in [53, 54].

In the present paper, we investigate the decay of the Higgs boson to a pair of the τ leptons with their consequent decay through the $\tau \to \pi\nu_\tau$ channel, namely the $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$ process. The case of a non-Hermitian interaction of the Higgs boson with the τ leptons is considered.

In Section 2, the full angular distribution of the pions is obtained. Then we derive the distribution of the angle between the $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\bar{\nu}_\tau$ decay planes, and the distribution of the polar angle of one of the pions in the helicity frame. The influence of non-Hermiticity of the $h\tau\tau$ interaction on the pion distributions is calculated and analyzed. In Section 3, the conclusions are presented.

2. Angular distributions of pions

We assume that the interaction of the Higgs boson (h) with the τ leptons is determined by the Lagrangian which includes scalar (S) and pseudoscalar (PS) parts

$$\mathcal{L}_{h\tau\tau} = -\frac{m_\tau}{v}\, h\, \bar{\psi}_\tau \left(a_\tau + i\, b_\tau \gamma_5\right) \psi_\tau\,, \tag{1}$$

where ψ_τ is the field of the fermion, $v = \left(\sqrt{2}G_{\rm F}\right)^{-1/2} \approx 246$ GeV is the vacuum expectation value of the Higgs field, $G_{\rm F} = 1.1663787(6) \times 10^{-5}$ GeV^{-2} is the Fermi constant [55], m_τ is the fermion mass, and a_τ, b_τ are complex parameters ($a_\tau = 1$ and $b_\tau = 0$ correspond to the SM). Equation (1) can be considered as a phenomenological parametrization of effects of new physics [11, 12, 26]. For the real-valued parameters a_τ, b_τ, the interaction (1) is Hermitian, however, we are interested in the case of non-Hermitian interaction with complex-valued parameters a_τ, b_τ. At the same time, the Higgs interaction with the $W^\pm$ and Z bosons is chosen Hermitian as in the SM.

Let us consider the decay of h to a pair of τ leptons with their consequent decay to the $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\bar{\nu}_\tau$ channels. The differential decay rate of $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$ in the Higgs boson rest frame can be written as

$$\begin{aligned} &\frac{{\rm d}^3\Gamma(h \to \tau^-\,\tau^+ \to \pi^-\nu_\tau\pi^+\bar{\nu}_\tau)}{{\rm d}\cos\theta_-{\rm d}\cos\theta_+{\rm d}\chi} \\ &= \Gamma(h \to \tau^-\tau^+) \times \left({\rm BR}(\tau \to \pi\nu_\tau)\right)^2 \frac{{\rm d}^3 W}{{\rm d}\cos\theta_-{\rm d}\cos\theta_+{\rm d}\chi}\,. \end{aligned} \tag{2}$$

Here, $\Gamma(h \to \tau^-\tau^+)$ is the Higgs boson decay width which in the leading order is given by

$$\Gamma\left(h \to \tau^-\tau^+\right) = m_h\,\beta_\tau \frac{G_{\rm F}\, m_\tau^2}{4\sqrt{2}\pi}\left(|a_\tau|^2\beta_\tau^2 + |b_\tau|^2\right)\,, \tag{3}$$

where m_h is the Higgs boson mass, $\beta_\tau = \sqrt{1 - 4m_\tau^2/m_h^2}$ is the velocity of the τ lepton in the rest frame of the Higgs, ${\rm BR}(\tau \to \pi\nu_\tau)$ is the branching of the τ decay through the $\tau \to \pi\nu_\tau$ channel. Further, the total angular distribution for the $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$ decay has the form of

$$\begin{aligned}\frac{\mathrm{d}^3 W}{\mathrm{d}\cos\theta_-\mathrm{d}\cos\theta_+\mathrm{d}\chi} = \frac{1}{8\pi}\Big(1 - \cos\theta_-\cos\theta_+ \\ - \frac{2\,\mathrm{Im}(a_\tau\, b_\tau^*)}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\,\beta_\tau\,(\cos\theta_- - \cos\theta_+) \\ - \frac{|a_\tau|^2\beta_\tau^2 - |b_\tau|^2}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\sin\theta_-\sin\theta_+\cos\chi \\ - \frac{2\,\mathrm{Re}(a_\tau\, b_\tau^*)}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\beta_\tau\,\sin\theta_-\sin\theta_+\sin\chi\Big)\,, \qquad (4)\end{aligned}$$

where θ_- (θ_+) is the angle between the direction of the π^- (π^+) meson motion in the τ^- (τ^+) lepton rest frame and the direction of the τ^- (τ^+) lepton motion in the h boson rest frame, and χ is the angle between the planes of the $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\bar{\nu}_\tau$ decays in the h boson rest frame (see Fig. 1).

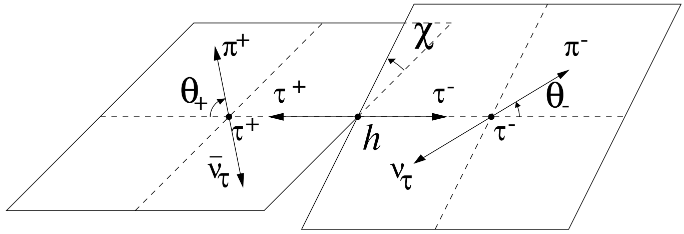

Fig. 1. Definition of helicity angles θ_-, θ_+, and χ in the sequential $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$ decay.

It is useful in parameterization of Eq. (4), instead of parameters a_τ, b_τ, to introduce the parameters (angles) ϕ_{CP} and ϕ_{H} defined as

$$\tan\phi_{\mathrm{CP}} \equiv \frac{|b_\tau|}{|a_\tau|}\,, \qquad (5)$$

$$\frac{2\,\mathrm{Im}(a_\tau\, b_\tau^*)}{|a_\tau|^2 + |b_\tau|^2} = \sin 2\phi_{\mathrm{CP}}\sin\phi_{\mathrm{H}}\,, \qquad (6)$$

$$\frac{2\,\mathrm{Re}(a_\tau\, b_\tau^*)}{|a_\tau|^2 + |b_\tau|^2} = \sin 2\phi_{\mathrm{CP}}\cos\phi_{\mathrm{H}}\,. \qquad (7)$$

As a result, Eq. (4) takes the form of

$$\frac{\mathrm{d}^3 W}{\mathrm{d}\cos\theta_-\mathrm{d}\cos\theta_+\mathrm{d}\chi} = \frac{1}{8\pi}\Big(1 - \cos\theta_-\cos\theta_+ - \frac{\beta_\tau \sin 2\phi_{\mathrm{CP}}\sin\phi_{\mathrm{H}}}{\beta_\tau^2\cos^2\phi_{\mathrm{CP}} + \sin^2\phi_{\mathrm{CP}}}(\cos\theta_- - \cos\theta_+) - \left(\frac{\beta_\tau^2\cos^2\phi_{\mathrm{CP}} - \sin^2\phi_{\mathrm{CP}}}{\beta_\tau^2\cos^2\phi_{\mathrm{CP}} + \sin^2\phi_{\mathrm{CP}}}\cos\chi + \frac{\beta_\tau \sin 2\phi_{\mathrm{CP}}\cos\phi_{\mathrm{H}}}{\beta_\tau^2\cos^2\phi_{\mathrm{CP}} + \sin^2\phi_{\mathrm{CP}}}\sin\chi\right) \times \sin\theta_-\sin\theta_+\Big) . \tag{8}$$

As the τ leptons produced in the decay of Higgs boson of the mass of 125 GeV are ultrarelativistic, one has $\beta_\tau \approx 0.9996$, and taking the limit $\beta_\tau \to 1$, we obtain

$$\frac{\mathrm{d}^3 W}{\mathrm{d}\cos\theta_-\mathrm{d}\cos\theta_+\mathrm{d}\chi} = \frac{1}{8\pi}\Big(1 - \cos\theta_-\cos\theta_+ - \sin 2\phi_{\mathrm{CP}}\sin\phi_{\mathrm{H}}(\cos\theta_- - \cos\theta_+) - (\cos 2\phi_{\mathrm{CP}}\cos\chi + \sin 2\phi_{\mathrm{CP}}\cos\phi_{\mathrm{H}}\sin\chi)\sin\theta_-\sin\theta_+\Big) . \tag{9}$$

For Hermitian $h\tau\tau$ interaction, $\phi_{\mathrm{H}} = 0$ or $\phi_{\mathrm{H}} = \pi$, Eq. (9) becomes

$$\frac{\mathrm{d}^3 W}{\mathrm{d}\cos\theta_-\mathrm{d}\cos\theta_+\mathrm{d}\chi} = \frac{1}{8\pi}\left(1 - \cos\theta_-\cos\theta_+ - \cos(\chi \pm 2\phi_{\mathrm{CP}})\sin\theta_-\sin\theta_+\right) . \tag{10}$$

Therefore, one of the observables with a maximal sensitivity to the correlations of the τ spins is the azimuthal angular correlation in the Higgs rest frame, which has a simple form [28] of

$$\frac{\mathrm{d}W}{\mathrm{d}\chi} = \frac{1}{2\pi}\left(1 - \frac{\pi^2}{16}\cos(\chi \pm 2\phi_{\mathrm{CP}})\right) . \tag{11}$$

For a non-Hermitian $h\tau\tau$ interaction (1), this angular correlation takes a different form of

$$\frac{\mathrm{d}W}{\mathrm{d}\chi} = \frac{1}{2\pi}\left(1 - \frac{\pi^2}{16}(\cos 2\phi_{\mathrm{CP}}\cos\chi + \sin 2\phi_{\mathrm{CP}}\cos\phi_{\mathrm{H}}\sin\chi)\right) . \tag{12}$$

One has to note that if it will not be possible to distinguish in experiments the events with the azimuthal angle χ from the events with the angle $2\pi - \chi$, then the resulting distribution of χ takes the form of

$$\frac{\mathrm{d}W}{\mathrm{d}\chi} = \frac{1}{\pi}\left(1 - \frac{\pi^2}{16}\cos 2\phi_{\mathrm{CP}}\cos\chi\right) , \qquad 0 \le \chi \le \pi . \tag{13}$$

In general, a possibility of measurement of the distribution (11) in experiments at the LHC or the ILC has been discussed by many authors with the aim of searching for violation of the $\mathcal{CP}$ symmetry in the $h \to \tau^- \tau^+$ decay (see, for example, [28, 29]). As for the influence of a non-Hermitian interaction (1) on the form of the distribution of the observable χ, this aspect has not been discussed.

In Figs. 2, 3, and 4, we show the angular distribution (12) for Hermitian and non-Hermitian interactions for a few values of the $\mathcal{CP}$-violation parameter $\phi_{\rm CP}$ and Hermiticity-violation parameter $\phi_{\rm H}$.

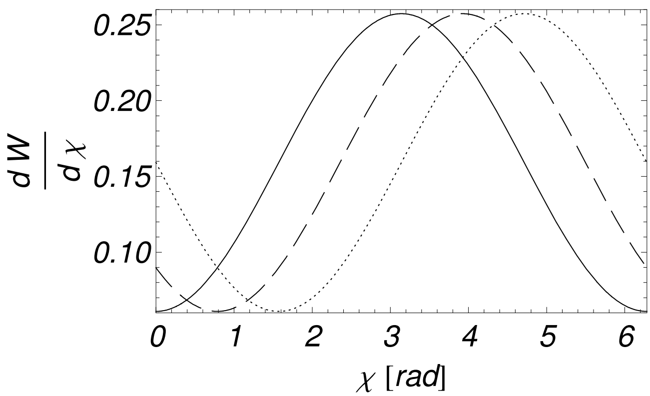

Fig. 2. Distribution of the azimuthal angle χ ($0 \le \chi \le 2\pi$) for Hermitian interaction with $\phi_{\rm H} = 0$. Solid line corresponds to the SM, dashed line — $\phi_{\rm CP} = \frac{\pi}{8}$, dotted line — $\phi_{\rm CP} = \frac{\pi}{4}$.

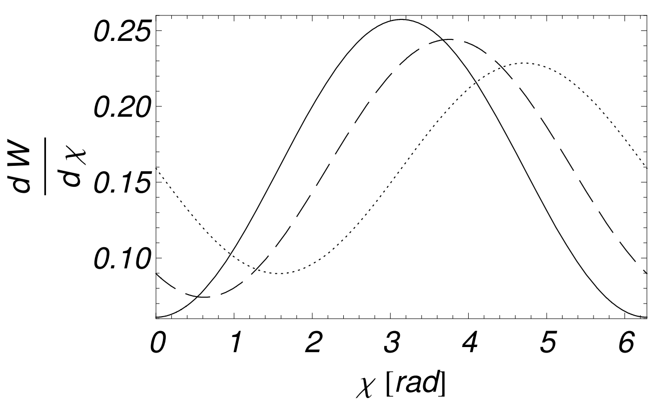

Fig. 3. Distribution of the azimuthal angle χ. Solid line — SM, dashed and dotted lines correspond to non-Hermitian interaction with $\phi_{\rm H} = \frac{\pi}{4}$: dashed line — $\phi_{\rm CP} = \frac{\pi}{8}$, dotted line — $\phi_{\rm CP} = \frac{\pi}{4}$.

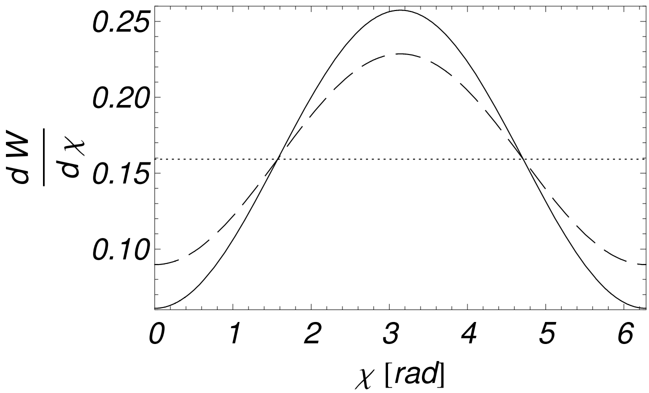

Fig. 4. Distribution of the azimuthal angle χ. Solid line — SM, dashed and dotted lines correspond to non-Hermitian interaction with $\phi_{\rm H} = \frac{\pi}{2}$: dashed line — $\phi_{\rm CP} = \frac{\pi}{8}$, dotted line — $\phi_{\rm CP} = \frac{\pi}{4}$.

It is seen from Fig. 2 that for the Hermitian interaction, one can measure violation of $\mathcal{CP}$ symmetry via the phase shift in the distribution of χ (11), if there is no background. If the interaction is non-Hermitian, then the azimuthal correlation (12) substantially differs from the SM case, as it is seen in Figs. 3 and 4, and the corresponding differences strongly depend on the parameter $\phi_{\rm H}$. A model for a non-Hermitian $h\tau\tau$ interaction in which $\phi_{\rm H} = \frac{\pi}{2}$ has been discussed in [26].

It would also be interesting to measure the following asymmetries:

$$A_1 \equiv \left(\int_0^{\pi/2} {\rm d}\chi - \int_{\pi/2}^{3\pi/2} {\rm d}\chi + \int_{3\pi/2}^{2\pi} {\rm d}\chi \right) \frac{{\rm d}W}{{\rm d}\chi} = -\frac{\pi}{8} \cos 2\phi_{\rm CP} \,, \tag{14}$$

$$A_2 \equiv \left(\int_0^{\pi} {\rm d}\chi - \int_{\pi}^{2\pi} {\rm d}\chi \right) \frac{{\rm d}W}{{\rm d}\chi} = -\frac{\pi}{8} \sin 2\phi_{\rm CP} \cos\phi_{\rm H} \,. \tag{15}$$

If the values of these asymmetries turn out to be different from the SM prediction, then this will be a clear signal of physics beyond the SM.

Finally, we briefly discuss another observable which is sensitive to non-Hermiticity of the Yukawa interaction. This is the polar-angle correlation

$$\frac{{\rm d}W}{{\rm d}\cos\theta_\pm} = \frac{1}{2} \left(1 \pm \sin 2\phi_{\rm CP} \sin\phi_{\rm H} \cos\theta_\pm \right) \,. \tag{16}$$

It follows from Eq. (16) that for Hermitian interaction ($\phi_{\rm H} = 0$ or $\phi_{\rm H} = \pi$), the distribution of the observable $\cos\theta_\pm$ is uniform. Therefore, any deviation of a measured distribution from 1/2 will point to a non-Hermiticity of the Yukawa interaction and violation of the $\mathcal{CP}$ symmetry in the Higgs boson decay to a pair of τ leptons.

3. Conclusions

In this work, we analyzed the differential rate of the decay of the Higgs boson to a pair of τ leptons with their subsequent decay into the $\tau^- \to \pi^- \nu_\tau$ and $\tau^+ \to \pi^+ \bar{\nu}_\tau$ channels. The Yukawa interaction between the Higgs boson and τ leptons is assumed to include both the scalar (S) and pseudoscalar (PS) couplings. The total angular distribution of the pions in the $h \to \tau^- \tau^+ \to \pi^- \nu_\tau \pi^+ \bar{\nu}_\tau$ process is considered, as well as distribution of the angle χ between the planes spanned by the $\tau^- \to \pi^- \nu_\tau$ and $\tau^+ \to \pi^+ \bar{\nu}_\tau$ decays, and distribution of the polar angle $\theta_\pm$ of the $\pi^\pm$.

For real values of the S and PS couplings, this decay is known to be a source of information on $\mathcal{CP}$ violation in the $h\tau\tau$ interaction. In the present work, we concentrate on a non-Hermitian Yukawa interaction. It is shown that the distributions of the charged pions strongly depend on a parameter of non-Hermiticity of the $h\tau\tau$ interaction. Asymmetries sensitive to parameters of $\mathcal{CP}$ violation and non-Hermiticity are proposed.

In summary, the measurement of the $h \to \tau^- \tau^+ \to \pi^- \nu_\tau \pi^+ \bar{\nu}_\tau$ decay allows one to test predictions of the SM, and can be a source of information on $\mathcal{CP}$ violation in the Yukawa interaction and on such a fundamental property as Hermiticity of this interaction.

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