CP-PROPERTIES OF A HIGGS BOSON IN THE $\Phi \to WW/ZZ \to 4$ FERMIONS PROCESSES IN THE TRANSVERSITY BASIS

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We examine the CP-violating effects and T-odd correlations for the most general ΦVV ($V = W^{\pm}$, Z) couplings through a study of the polarization effects in the processes $\Phi \to WW/ZZ \to 4$ fermions in the transversity basis. We have shown that, in order to measure the Higgs boson parity, it is convenient to use the distribution of the process $\Phi \to Z\,Z \to (e^- e^+)\,(\mu^- \mu^+)$ over the azimuthal angle in the transversity basis.

1. Introduction

The search for a Higgs particle (H-boson), which is foreseen by the theory of electroweak interactions of leptons and hadrons, is one of the main purposes of the Large Hadron Collider (LHC) in CERN. After the observation of events which will be identified as the creation and the decay of the Higgs boson, it will be necessary to determine the quantum numbers J^{PC}, i.e. the spin, P-parity, and C-parity of the Higgs boson.

In the standard model (SM), only one neutral Higgs boson, H, with the quantum numbers 0^{++} is predicted. At the same time, a number of unified models of field theory which possess a more complicated structure of the Higgs sector are developed. For example, the model of minimal supersymmetric extension of SM or the minimal supersymmetric standard model (MSSM) includes three neutral Higgs bosons, two of which are CP-even (h, H), and one boson is CP-odd (A) relative to the CP-conjugation, and two charged bosons ($H^{\pm}$) (see, e.g., [1]). Though the CP-invariance cannot be spontaneously broken by the "self-interaction" of Higgs fields on the "tree" level in MSSM, nevertheless, the violation of CP-invariance can be induced by radiative corrections to the Higgs potential [2]. As a result, three physical neutral Higgs bosons will not have a definite CP-parity. In nonsupersymmetric models with the nonminimal Higgs sector, e.g., in the most general model of the interaction of two doublets of Higgs fields (2HDM) (see, e.g., [3]), and also in supersymmetric models with the additional singlet of scalar fields [4, 5], the Higgs sector can cause the violation of CP-invariance. Thus, the determination of CP-properties of the Higgs boson (bosons) will be an important stage in the study of the mechanism of spontaneous breaking of a symmetry of the electroweak interaction.

In studying the CP-properties of the Higgs boson (bosons), one can use characteristic features of the differential cross-section of the process of its creation and/or angular and energy distributions of products of its decay. We consider the decays of Higgs bosons into a pair of vector ($W^-\,W^+$ or $Z\,Z$) bosons which succesively decay into two pairs of nonidentical fermions (leptons and quarks),

$$\Phi \to V_1\,V_2 \to (f_1 \bar{f}_2)\,(f_3 \bar{f}_4), \tag{1}$$

where Φ is the general notation of the Higgs boson which has no definite CP-parity, whereas the Higgs bosons H and A are, respectively, CP-even and CP-odd.

The cascade process of decay

$$H \to Z\,Z \to (e^-\,e^+)\,(\mu^-\,\mu^+) \tag{2}$$

is extremely important for LHC at the mass of the Higgs boson $M > 2\,M_Z$ for both the measurement of the mass of the Higgs boson and the determination of its spin and P-parity [6–8]. In addition, the study of the angular distributions of products of decay (2) will allow one to

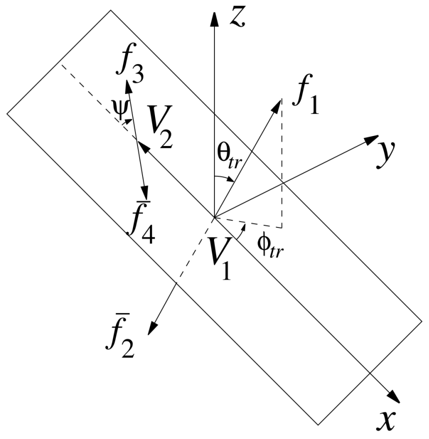

Fig. 1. Determination of angles in the transversity basis. The angles $\theta_{\rm tr}$ and $\phi_{\rm tr}$ are measured in the rest system of the V_1-boson, whereas the angle ψ is determined in the rest system of V_2-boson

investigate manifestations of the possible CP-violation in the decay $H \to Z\,Z$ [9, 10].

The angular distributions of products of decay (1) were analyzed in works [6–10] in the helicity system. As the amplitude of the decay $\Phi \to V_1\,V_2$, its representation with the help of invariant or helicity amplitudes was used. However, while studying the structure of three-boson $\Phi\,W^+W^-$- and $\Phi\,ZZ$-vertices, it is most convenient to represent it by using the linear-polarization (transverse-polarization) states of vector bosons, because they are eigenfunctions of the operator of space reflection, and their bilinear combinations have a clear physical sense: they are components of the polarization and the coefficients of correlation between the polarization states of vector bosons ($W^\pm$ and Z).

In the present work, we will consider the most general structure of the interaction of the Higgs Φ-boson with two intermediate vector bosons ($W^-\,W^+$ and $Z\,Z$) and obtain the angular distributions of products of decay (1) in the transversity system of coordinates (see Fig. 1). Moreover, the amplitude of the decay $\Phi \to V_1\,V_2$ will be represented in the transversity basis as well. The comparison of those distributions with experimental data will allow us to establish the structure of three-boson $\Phi\,W^+W^-$- and $\Phi\,ZZ$-vertices. The results obtained can be used for the determination of the P-parity of the Higgs boson and the search for effects of the violation of CP- and T-invariances in the decays $\Phi \to V_1\,V_2$.

2. Amplitude of the Decay $\Phi \to V_1\,V_2$

Consider the decay of the Higgs Φ-boson (with zero spin) into a pair of vector ($W^-\,W^+$ or $Z\,Z$) bosons, $\Phi(p) \to V_1(p_1,\,\epsilon_1)V_2(p_2,\,\epsilon_2)$. The most general covariant amplitude for this decay has the form

$$\mathcal{A}(\Phi \to V_1\,V_2) = g_V\Big(a\,\epsilon_1^*\cdot\epsilon_2^* + \frac{b}{M^2}(\epsilon_1^*\cdot p)(\epsilon_2^*\cdot p)+$$

$$+i\frac{c}{M^2}\varepsilon_{\mu\nu\rho\sigma}p^\mu q^\nu \epsilon_1^{*\rho}\epsilon_2^{*\sigma}\Big), \qquad (3)$$

where p is the 4-momentum of the Φ-boson, p_1, p_2 are the 4-vectors of the momenta, ϵ_1 and ϵ_2 are the 4-vectors of the polarization of vector V_1 and V_2 bosons, respectively, $g_Z \equiv g_2\,M_Z/\cos\theta_W,\ g_W \equiv g_2\,M_W,\ g_2^2/(8\,M_W^2) = G_F/\sqrt{2},\ M_W/M_Z = \cos\theta_W,\ \theta_W$ is the weak mixing angle, M and $M_W(M_Z)$ are the masses of Φ and W-(Z-) boson, G_F is the constant of the Fermi weak interaction, $q = p_1 - p_2$, and $\varepsilon_{\mu\nu\rho\sigma}$ is the completely antisymmetric tensor with $\varepsilon_{0123} = 1$.

In the frame of SM, $a = 1$ and $b = c = 0$. For the decay of a pseudoscalar Φ-boson: $c \neq 0$ and $a = b = 0$. If formula (3) will include not only c, but at least one of the quantities a and b, then a Φ-boson will not possess a certain P-parity.

In the general case, the amplitude of the decay $\Phi \to V_1\,V_2$ depends on the quantities a, b, and c which can arise due to radiative corrections or the "new physics" on the TeV-scale, i.e. due to the operators with higher dimensionalities [11, 12]. The quantities a, b, and c can be complex-valued and involve two types of phases: the phases invariable at the CP-transformation and those whose sign becomes opposite at the CP- transformation.

We note that the phases invariable at the CP-transformation can appear in the process of decay due to the final-state interaction which is invariant relative to CP-transformations, whereas the the phases, whose sign is changed by the opposite one at the CP-transformation, can arise in the presence of complex-valued parameters of the interaction potential of scalar fields [2, 13].

The decay of a Φ-boson with zero spin into a pair of vector bosons $\Phi \to V_1\,V_2$ is characterized by three amplitudes. In order to easier determine the CP-odd and CP-even or $\tilde{T}$-odd and $\tilde{T}$-even components (where $\tilde{T}$ means the "naive" inversion of time, when the momentum and the spin of a particle are changed by those of the opposite directions, but the initial and final states of the process are invariable) from this decay, it is convenient to write the amplitude of the decay $\Phi \to V_1\,V_2$ in terms of the linear-polarization (transverse-polarization) states of vector bosons, which are or longitudinal (A_0) or transverse to the direction of their motion and parallel ($A_\parallel$) or perpendicular ($A_\perp$) to each other. Thus, the amplitude of the decay $\Phi(p) \to V_1(p_1,\, \epsilon_1)\, V_2(p_2,\, \epsilon_2)$ can be written as

$$\mathcal{A}(\Phi \to V_1\, V_2) = g_V\Big(\frac{A_0}{x}\,\epsilon_1^{*L}\epsilon_2^{*L} - \frac{A_\parallel}{\sqrt{2}}\,\boldsymbol{\epsilon}_1^{*T}\cdot\boldsymbol{\epsilon}_2^{*T} - -i\frac{A_\perp}{\sqrt{2}}\,\boldsymbol{\epsilon}_1^{*T}\times\boldsymbol{\epsilon}_2^{*T}\cdot\hat{\mathbf{p}}\Big), \quad (4)$$

where $\hat{\mathbf{p}}$ is the unit vector along the motion direction of a V_2-boson in the rest system of a V_1-boson, $\epsilon_i^{*L} \equiv \boldsymbol{\epsilon}_i^{*}\cdot\hat{\mathbf{p}}$, and $\boldsymbol{\epsilon}_i^{*T} = \boldsymbol{\epsilon}_i^{*} - \epsilon_i^{*L}\hat{\mathbf{p}}$, $i = 1,\, 2$.

In relation (4), $x \equiv \gamma^2(1+\beta^2)$, $\beta \equiv \sqrt{1-4\,x_V}$ is the velocity of vector bosons in the rest system of the Higgs boson, $x_V \equiv M_V^2/M^2$, M_V is the mass of vector bosons, $\gamma \equiv 1/\sqrt{1-\beta^2}$ is the Lorentz-factor. The quantity $A_\perp$ is P-odd, whereas the quantities A_0 and $A_\parallel$ are P-even. The quantities A_0, $A_\parallel$ and $A_\perp$ are related to the quantities a, b, and c in (3) in the following way:

$$A_0 = -\gamma^2(a\,(1+\beta^2)+b\,\beta^2),\; A_\parallel = \sqrt{2}\,a,\; A_\perp = \sqrt{2}\,\beta\,c. \quad (5)$$

For the decay $\Phi \to V_1\, V_2$, the amplitude A_λ, where the index λ takes the values $\{0, \parallel, \perp\}$, has the form

$$A_\lambda = \sum_k a_\lambda^k\, e^{i(\phi_k+\delta_\lambda^k)}, \quad (6)$$

where the summation is executed over all Feynman diagrams which contribute to this decay, ϕ_k is the phase, whose sign is changed by the opposite one at the CP-transformation of the k-th diagram, δ_λ^k are the phases invariable at the CP-transformation of the k-oï diagram. The quantities a_λ^k, ϕ_k, and δ_λ^k are real. The amplitude of the CP-conjugated process of decay $\bar\Phi(p) \to \bar V_1(p_1,\, \epsilon_1)\, \bar V_2(p_2,\, \epsilon_2)$ is defined analogously to (4) with the replacement of A_λ by $\bar A_\lambda$, and

$$\bar A_\lambda = \sigma_\lambda \sum_k a_\lambda^k\, e^{i(-\phi_k+\delta_\lambda^k)}, \quad (7)$$

where $\sigma_0 = \sigma_\parallel = 1$ and $\sigma_\perp = -1$.

If the decay $\Phi \to V_1\, V_2$ is invariant relative to CP-transformations, i.e. $\phi_k = 0$, then $\bar A_0 = A_0$, $\bar A_\parallel = A_\parallel$, and $\bar A_\perp = -A_\perp$. We note that if the final-state interaction is absent, i.e. $\delta_\lambda^k = 0$, then $\bar A_0 = A_0^*$, $\bar A_\parallel = A_\parallel^*$, and $\bar A_\perp = -A_\perp^*$. We norm the partial widths for three independent polarization states in such a way that

$$\Gamma(\Phi \to V_1 V_2) = \frac{G_F M^3}{2\sqrt{2}\pi}\delta_V x_V^2\Big(|A_0|^2+|A_\parallel|^2+|A_\perp|^2\Big)\beta, \quad (8)$$

where $\Gamma(\Phi \to V_1\, V_2)$ is the width of the decay $\Phi \to V_1 V_2$, $\delta_W = 1$ for $V_1\, V_2 = W^+ W^-$, and $\delta_Z = 1/2$ for $V_1\, V_2 = Z\, Z$.

Thus, the partial widths of the decays $\Phi \to V_1\, V_2$ and $\bar\Phi \to \bar V_1\, \bar V_2$ will be the same both at the conservation of CP-invariance in these decays and at the violation of CP-invariance but in the absence of the final-state interaction. We note that the quantities A_0, $A_\parallel$, and $A_\perp$ in SM have the form

$$A_0 = -\gamma^2(1+\beta^2),\; A_\parallel = \sqrt{2},\; A_\perp = 0. \quad (9)$$

The explicit expression for the angular distribution of products of decay (1) depends on the system of coordinates. We represent it in the transversity system and, as the amplitude of the decay $\Phi \to V_1\, V_2$, will use its representation through the linear-polarization states of vector bosons ($W^\pm$ and Z).

3. Angular Distributions of Products of the Decay $\Phi \to V_1\, V_2$ in the Transversity System

In the transversity system shown in Fig. 1, the angular distribution of process (1) can be presented in the form of a function of $\theta_{\rm tr}$, ψ, and $\phi_{\rm tr}$. In this case, the motion direction of the V_1-boson in the rest system of the Φ-boson defines the axis x, and the system of fermions $f_3\,\bar f_4$ defines the plane $x-y$ with the axis y so that $p_y(f_3) > 0$. The axis z is taken in the rest system of the V_1-boson normally to the plane which includes the system $f_3\,\bar f_4$, by using the right system of coordinates. The transverse angles $\theta_{\rm tr}$ and $\phi_{\rm tr}$ are the polar and azimuthal angles of the momentum of the f_1-fermion in this system. The angle ψ is the helicity angle between the momentum of the f_3-fermion in the rest system of the V_2-boson and the direction opposite to the momentum of the V_1-boson in the rest system of the V_2-boson.

In the transversity system, the total angular distribution of process (1) has the form

$$\frac{1}{\Gamma}\frac{d^3\Gamma(\Phi \to V_1\, V_2 \to (f_1\bar f_2)\,(f_3\bar f_4))}{d\cos\theta_{\rm tr}\, d\cos\psi\, d\phi_{\rm tr}} = \frac{9}{64\,\pi}\Big(2R_L(1- -\sin^2\theta_{\rm tr}\cos^2\phi_{\rm tr})\sin^2\psi + R_\parallel\Big(\sin^2\theta_{\rm tr} + \cos^2\psi - -\sin^2\theta_{\rm tr}\cos^2\psi\sin^2\phi_{\rm tr} + 2A_f A_{f'}\sin\theta_{\rm tr}\cos\psi\cos\phi_{\rm tr}\Big) + +R_\perp\Big(1 + \sin^2\theta_{\rm tr}\cos^2\psi - \sin^2\theta_{\rm tr}\sin^2\phi_{\rm tr} + 2A_f A_{f'}\times$$

$$\times \sin\theta_{\rm tr}\cos\psi\cos\phi_{\rm tr}\Big) - \xi_{\perp\parallel}\sin 2\theta_{\rm tr}\sin^2\psi\sin\phi_{\rm tr} + \frac{\xi_{\parallel 0}}{\sqrt{2}}\times$$
$$\times\Big(\sin^2\theta_{\rm tr}\sin 2\psi\sin 2\phi_{\rm tr} + 4A_f A_{f'}\sin\theta_{\rm tr}\sin\psi\sin\phi_{\rm tr}\Big)-$$
$$-\frac{\xi_{\perp 0}}{\sqrt{2}}\Big(\sin 2\theta_{\rm tr}\sin 2\psi\cos\phi_{\rm tr} + A_f A_{f'}\cos\theta_{\rm tr}\sin\psi\Big)-$$
$$-2\sqrt{2}\Big(\zeta_{\perp 0}\sin\theta_{\rm tr}\sin\phi_{\rm tr} - \zeta_{\parallel 0}\cos\theta_{\rm tr}\Big)\Big(A_{f'}\sin\theta_{\rm tr}\times$$
$$\times\cos\phi_{\rm tr} + A_f\cos\psi\Big)\sin\psi - 2\zeta_{\perp\parallel}\Big(A_f(1+\cos^2\psi)\times$$
$$\times\sin\theta_{\rm tr}\cos\phi_{\rm tr} + A_{f'}(1+\sin^2\theta_{\rm tr}\cos^2\phi_{\rm tr})\cos\psi\Big)\Big), \quad (10)$$

where

$$R_L \equiv \frac{|A_0|^2}{\sum\limits_{\lambda=0,\parallel,\perp}|A_\lambda|^2},\ R_\parallel \equiv \frac{|A_\parallel|^2}{\sum\limits_\lambda |A_\lambda|^2},\ R_\perp \equiv \frac{|A_\perp|^2}{\sum\limits_\lambda |A_\lambda|^2},$$

$$\xi_{\perp i} \equiv \frac{\Im(A_\perp A_i^*)}{\sum\limits_\lambda |A_\lambda|^2},\quad \xi_{\parallel 0} \equiv \frac{\Re(A_\parallel A_0^*)}{\sum\limits_\lambda |A_\lambda|^2},$$

$$\zeta_{\perp i} \equiv \frac{\Re(A_\perp A_i^*)}{\sum\limits_\lambda |A_\lambda|^2},\quad \zeta_{\parallel 0} \equiv \frac{\Im(A_\parallel A_0^*)}{\sum\limits_\lambda |A_\lambda|^2}, \quad (11)$$

$i = 0, \parallel$. The coefficient R_L stands for the longitudinal polarization of the V_1-boson, and $R_\perp (R_\parallel)$ is the component of the transverse polarization of the V_1-boson along the axis z (axis y)(see Fig. 1). The quantities $\xi_{\perp i}$, $\xi_{\parallel 0}$, $\zeta_{\perp i}$, and $\zeta_{\parallel 0}$ are the coefficients of correlation between the linear-polarization states of vector bosons. For the decay $\Phi \to Z\,Z \to (f\bar f)\,(f'\bar f')$ in (10): $f \equiv f_1$, $f' \equiv f_3$, $\bar f \equiv \bar f_2$, $\bar f' \equiv \bar f_4$ and

$$A_f \equiv \frac{2\,g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2},\ A_{f'} \equiv \frac{2\,g_V^{f'} g_A^{f'}}{(g_V^{f'})^2 + (g_A^{f'})^2}.$$

The vector and axial-vector constants, respectively, have the form $g_V^f \equiv t_{3L}(f) - 2\,Q(f)\,\sin^2\theta_W$ and $g_A^f \equiv t_{3L}(f)$, where $t_{3L}(f)$ is the projection of the weak isotopic spin of the f-fermion, $Q(f)$ is the charge of the f-fermion in units of the electric charge of a positron. For the decay $\Phi \to W^-\,W^+ \to (f_1\bar f_2)\,(f_3\bar f_4)$ in (10), we have $A_f = A_{f'} = 1$ if $W^\pm$-bosons decay into two pairs of leptons; but if $W^\pm$-bosons decay into two pairs of quarks, A_f and $A_{f'}$ are equal to the corresponding elements of the Cabibbo–Kobayashi–Maskawa mixing matrix for quarks [14].

The observables R_L, $R_\parallel$, $R_\perp$, $\xi_{\parallel 0}$, $\xi_{\perp i}$, $\zeta_{\parallel 0}$, and $\zeta_{\perp i}$ which are the coefficients of the dynamical variables can be classified according to the properties of these variables relative to the P-inversion of coordinates (the mirror reflection) and the "naive" $\tilde T$-inversion of time. The observables R_L, $R_\parallel$, $R_\perp$, and $\xi_{\parallel 0}$ are P-even and $\tilde T$-even, $\xi_{\perp 0}$ and $\xi_{\perp\parallel}$ are P-odd and $\tilde T$-odd, $\zeta_{\parallel 0}$ is P-even and $\tilde T$-odd, $\zeta_{\perp 0}$ and $\zeta_{\perp\parallel}$ are P-odd and $\tilde T$-even. We note that, for the decay of B-mesons into a pair of vector mesons, the classification of properties of the observables relative to the inversion of coordinates and the "naive" inversion of time was implemented in [15].

The angular distribution for the CP-conjugated decay $\bar\Phi \to \bar V_1\,\bar V_2$ is determined by formula (10) with the replacement of A_λ by $\bar A_\lambda$ in (11). If the decay $\Phi \to V_1\,V_2$ is invariant relative to the CP-transformations, then the angular distribution $\bar I(\theta_{\rm tr}, \psi, \phi_{\rm tr})$ for the decay $\bar\Phi \to \bar V_1\,\bar V_2$ coincides with the angular distribution $I(\pi - \theta_{\rm tr}, \pi - \psi, \pi - \phi_{\rm tr})$ for the decay $\Phi \to V_1\,V_2$, i.e. $\bar I(\theta_{\rm tr}, \psi, \phi_{\rm tr}) = I(\pi - \theta_{\rm tr}, \pi - \psi, \pi - \phi_{\rm tr})$. Moreover, we have $\bar R_L = R_L$, $\bar R_\parallel = R_\parallel$, $\bar R_\perp = R_\perp$, $\bar\xi_{\perp i} = -\xi_{\perp i}$, $\bar\xi_{\parallel 0} = \xi_{\parallel 0}$, $\bar\zeta_{\perp i} = -\zeta_{\perp i}$ and $\bar\zeta_{\parallel 0} = \zeta_{\parallel 0}$.

Thus, we can construct a great number of observables for decay (1), whose nonzero values will indicate the violation of CP-invariance, namely: $\bar R_L - R_L$, $\bar R_\parallel - R_\parallel$, $\bar R_\perp - R_\perp$, $\bar\xi_{\perp i} + \xi_{\perp i}$, $\bar\xi_{\parallel 0} - \xi_{\parallel 0}$, $\bar\zeta_{\perp i} + \zeta_{\perp i}$ and $\bar\zeta_{\parallel 0} - \zeta_{\parallel 0}$. We note that if the final-state interaction for the decay $\Phi \to V_1 V_2$ is absent, quantities (11) will satisfy the following relations: $\bar R_L = R_L$, $\bar R_\parallel = R_\parallel$, $\bar R_\perp = R_\perp$, $\bar\xi_{\perp i} = \xi_{\perp i}$, $\bar\xi_{\parallel 0} = \xi_{\parallel 0}$, $\bar\zeta_{\perp i} = -\zeta_{\perp i}$, and $\bar\zeta_{\parallel 0} = -\zeta_{\parallel 0}$. In this case, the nonzero values of the observables $\xi_{\perp i}$ and $\zeta_{\parallel 0}$ will testify to the violation of both the CP- and T-invariances. Whereas the nonzero values of the quantities which indicate the violation of CP-invariance, $\bar R_L - R_L$, $\bar R_\parallel - R_\parallel$, $\bar R_\perp - R_\perp$, $\bar\xi_{\parallel 0} - \xi_{\parallel 0}$, and $\bar\zeta_{\perp i} + \zeta_{\perp i}$ will be possible only in the presence of the final-state interaction for the reaction $\Phi \to V_1\,V_2$ which should not be significant for the processes under consideration. For example, the account of radiative corrections to the decay $H \to WW/ZZ \to 4\,$leptons in the frame of SM showed that they are usually equal to several percent of the decay width and increase with increase in the Higgs boson mass, by attaining 8 % at the mass $M_H \sim 500$ GeV [16].

After the discovery of the Higgs boson, it will be necessary to study the structure of three-boson $\Phi\,W^-W^+$- and $\Phi\,ZZ$-interactions. The investigation of the total angular distribution of the process of decay (1) will allow one to establish the values of the observables R_L, $R_\parallel$, $R_\perp$, $\xi_{\parallel 0}$, $\xi_{\perp i}$, $\zeta_{\parallel 0}$, and $\zeta_{\perp i}$ and, thus, to determine the structure of three-boson $\Phi\, W^- W^+$- and $\Phi\, ZZ$-interactions, and to answer the question about the possible violation of *CP*-invariance in the decay $\Phi \to V_1\, V_2$. To realize such a study, it should be necessary to have the sufficient number of events of process (1). Therefore, it is expedient to establish which information about the structure of three-boson $\Phi\, W^- W^+$- and $\Phi\, ZZ$-interactions can be obtained in the study of the one-dimensional angular distributions of process (1): in the first turn, the information about its difference from the predictions of SM and also about the *P*-parity of the Higgs Φ-boson and the possible violation of the *CP*-invariance in the decay $\Phi \to V_1\, V_2$.

We consider three one-dimensional distributions: over the cosine of the helicity angle ψ, over the cosine of the transverse angle $\theta_{\rm tr}$, and over the azimuthal angle $\phi_{\rm tr}$ (see Fig. 1). These distributions depend on the mechanism of decay of the Higgs boson into a pair of vector bosons. For illustration, the Table presents the values of components of the polarization and the coefficients of correlation between the polarization states of the Z-boson created in the process $\Phi \to Z\, Z$ for different mechanisms of the interaction of the Higgs boson with the pair of intermediate vector Z-bosons. In what follows, we will use these values for the numerical estimation of asymmetries.

By performing the integration of (10) over the angles $\theta_{\rm tr}$ and $\phi_{\rm tr}$, we obtain the following formula for the distribution over the helicity angle ψ between the momentum of the f_3-fermion in the rest system of the V_2-boson and the motion direction of the V_2-boson in the rest system of the Φ-boson:

$$\frac{1}{\Gamma}\frac{d\Gamma(\Phi \to V_1\, V_2 \to (f_1 \bar f_2)\, (f_3 \bar f_4))}{d\cos\psi} = \frac{3}{8}\Big(2R_L \sin^2\psi + +(R_\parallel + R_\perp)(1+\cos^2\psi) - 4A_{f'}\zeta_{\perp\parallel}\cos\psi\Big). \qquad (12)$$

The measurement of the asymmetry "forward-backward" $\mathcal{A}_{\rm FB}$ relative to the motion direction of the V_2-boson in the rest system of the Φ-boson for f_3-fermions created in decay (1),

$$\mathcal{A}_{\rm FB} \equiv \frac{\mathcal{F}-\mathcal{B}}{\mathcal{F}+\mathcal{B}},\ \mathcal{F} \equiv \int\limits_0^1 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\psi}\, d\cos\psi,$$

$$\mathcal{B} \equiv \int\limits_{-1}^0 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\psi}\, d\cos\psi, \qquad (13)$$

which equals $-3A_{f'}\,\zeta_{\perp\parallel}/2$, allows one to determine the quantity $\zeta_{\perp\parallel}$.

We note that, for the decay $\Phi \to Z\, Z \to (e^- e^+)\, (\mu^- \mu^+)$, the quantity A_μ is approximately equal to 0.15 [17]. Moreover, in view of the fact that the parameter $\zeta_{\perp\parallel}$ satisfies the inequality $|\zeta_{\perp\parallel}| \le \sqrt{R_\perp R_\parallel} \le 1/2$, we get that the absolute value of the asymmetry for this decay will not exceed 0.11. For the channel $\Phi \to Z\, Z \to (e^- e^+)\, (b\, \bar b)$ (due to the fact that $A_b = 0.923$ [17]), the absolute value of this asymmetry can be much greater; namely, it can attain 0.69. For example, for $M = 200$ GeV and at $a = c = 1$, $b = 0$, it will be equal to -0.26. We note that, for the channel $\Phi \to Z\, Z \to (e^- e^+)\, (\mu^- \mu^+)$, it is only -0.04.

The shares of the longitudinal and transverse polarizations of vector bosons in the decay $\Phi \to V_1 V_2$ can be measured, if one will compare distribution (12) with experimental data (by using the method of maximum likelihood) or will measure the mean values of the functions $2 - 5\cos^2\psi$ and $5\cos^2\psi - 1$, because, for such mean values, we have $\langle 2 - 5\cos^2\psi\rangle = R_L$ and $\langle 5\cos^2\psi - 1\rangle = R_\parallel + R_\perp$, (we note also that $\langle\cos\psi\rangle = -A_{f'}\,\zeta_{\perp\parallel}$). Thus, the study of the distribution of process

Values of components of the polarization and the correlation coefficients between the polarization states of a Z-boson created in the decay $\Phi \to ZZ$ at some values of the parameters a, b, and c and at the Higgs boson masses, respectively, of 200 and 400 GeV

Values of a, b, and c	R_L	$R_\parallel$	$R_\perp$	$\xi_{\parallel 0}$	$\xi_{\perp 0}$	$\xi_{\perp\parallel}$	$\zeta_{\parallel 0}$	$\zeta_{\perp 0}$	$\zeta_{\perp\parallel}$
$a=1,\ b=c=0$	0.5	0.5	0	−0.5	0	0	0	0	0
	0.97	0.03	0	−0.16	0	0	0	0	0
$a=1,\ b=0,\ c=1$	0.46	0.46	0.08	−0.46	0	0	0	−0.19	0.19
	0.95	0.03	0.02	−0.16	0	0	0	−0.14	0.02
$a=1,\ b=0,\ c=i$	0.46	0.46	0.08	−0.46	−0.19	0.19	0	0	0
	0.95	0.03	0.02	−0.16	−0.14	0.02	0	0	0
$a=1,\ b=i,\ c=1$	0.46	0.46	0.08	−0.46	0.03	0	0.07	−0.19	0.19
	0.96	0.02	0.02	−0.13	0.05	0	0.06	−0.12	0.02
$a=1,\ b=c=i$	0.46	0.46	0.08	−0.46	−0.19	0.19	0.07	−0.03	0
	0.96	0.02	0.02	−0.13	−0.12	0.02	0.06	−0.05	0

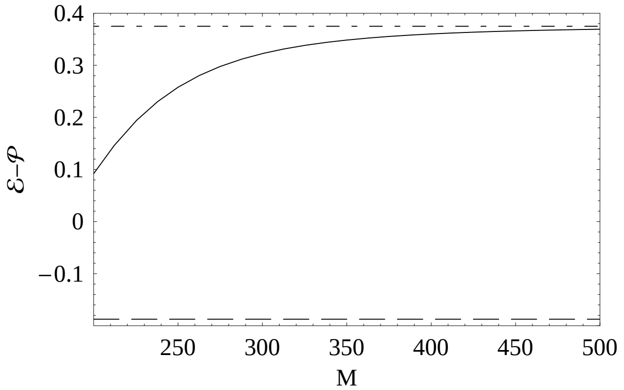

Fig. 2. Expected value of the difference $\mathcal{E}$ and $\mathcal{P}$ for the decay $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ at various masses M (GeV) of the Higgs boson. Solid line corresponds to the Higgs boson in SM ($a = 1$, $b = c = 0$), dashed line – to the CP-odd state ($a = b = 0$, $c \neq 0$), and the dash-dotted line – to the CP-even state ($a = c = 0$, $b \neq 0$)

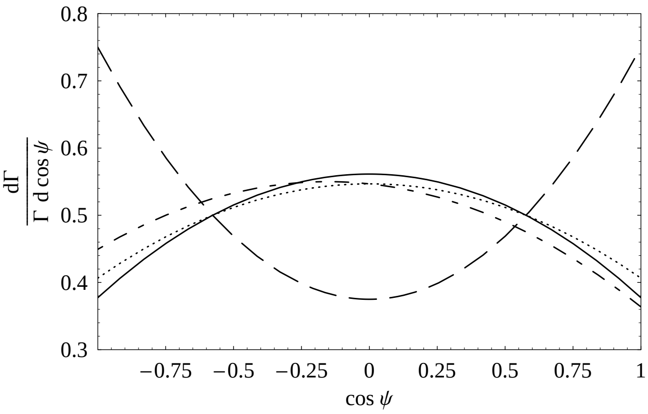

Fig. 3. Angular distribution over $\cos\psi$ of the process $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ in the transversity system. Solid line corresponds to SM ($a = 1$, $b = c = 0$), dashed line – to the pure pseudoscalar state ($a = b = 0$, $c \neq 0$), and the dash-dotted and dotted lines correspond to a mixture of CP-even and CP-odd states ($a = 1$, $b = 0$, $c = 1$) and ($a = 1$, $b = 0$, $c = i$), respectively. The mass of the Higgs boson is 200 GeV

(1) over the cosine of the helicity angle ψ can allow one to determine the value of the longitudinal, R_L, and transverse, $R_T = R_\parallel + R_\perp$, polarizations of vector bosons but does not allow one to determine separate values of the polarizations $R_\parallel$ and $R_\perp$ of vector bosons.

For the determination of the P-parity of the Higgs boson, it is necessary to measure the number of events of process (1) which fall into the interval $-1/2 \leq \cos\psi \leq 1/2$ and into the intervals $-1 \leq \cos\psi \leq -1/2$ and $1/2 \leq \cos\psi \leq 1$, i.e.

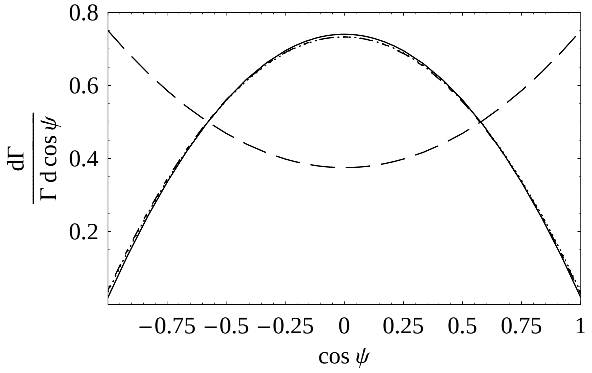

Fig. 4. The same as in Fig. 3, but for the Higgs boson mass equal to 400 GeV

$$\mathcal{E} \equiv \int\limits_{-1/2}^{1/2} d\cos\psi\, \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\psi},$$

$$\mathcal{P} \equiv \left(\int\limits_{-1}^{-1/2} d\cos\psi + \int\limits_{1/2}^{1} d\cos\psi \right) \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\psi}$$

and to determine their difference $\mathcal{E} - \mathcal{P}$ which equals $3(3\,R_L - 1)/16$.

In SM, the difference $(\mathcal{E} - \mathcal{P})_{sm} \geq 0$. Moreover, it takes the zero value at the threshold of the decay $H \to V_1\,V_2$, whereas this quantity will have a negative value of $-3/16$ for the pseudoscalar Higgs boson. In Fig. 2, we show the expected value of the difference of the quantities $\mathcal{E}$ and $\mathcal{P}$ for the decay $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ at various masses of the Higgs boson in SM, for the CP-odd Higgs boson, and for one of the possible CP-even states of the Higgs boson.

We note that amplitude (3) at $c = 0$ describes the decay of the 0^+-state into a pair of vector bosons (we recall that, in the frame of SM, $a = 1$ and $b = 0$). However, in the general case, the parameters a and b can take any values. Therefore, (depending on the values of these parameters) vector bosons can be created in the states with $R_L = 1$ (in this case, $\mathcal{E} - \mathcal{P} = 3/8$; this state is shown in Fig. 2), $R_\parallel = 1$ ($\mathcal{E} - \mathcal{P} = -3/16$), and $R_L + R_\parallel = 1$. By measuring the difference $\mathcal{E} - \mathcal{P}$, one can determine the share of the longitudinal polarization of vector bosons: $R_L = 1/3 + 16(\mathcal{E} - \mathcal{P})/9$. Moreover, if the Higgs boson mass is known from the previous measurements, it is possible to establish whether the observed resonance is just the Higgs boson in SM.

It is seen from Figs. 3 and 4 that if the CP-invariance is preserved in the decay $\Phi \to Z\,Z$, there exist the sharp differences in the form of the angular distribution over $\cos\psi$ for the process $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ for the Higgs boson in SM and for the pure pseudoscalar resonance at the masses of the Higgs boson $M = 200$ GeV and $M = 400$ GeV, which can be used for the determination of the CP-parity of the Higgs boson. On the other hand, the difference between the angular distributions for the Higgs boson in SM and under the possible violation of CP-invariance in the decay $\Phi \to ZZ$ depends essentially on the values of the constants a, b, and c and on the Higgs boson mass.

The angular distribution over $\cos\theta_{\rm tr}$ for decay (1) can be represented in the form

$$\frac{1}{\Gamma}\frac{d\Gamma(\Phi \to V_1\,V_2 \to (f_1\bar{f}_2)\,(f_3\bar{f}_4))}{d\cos\theta_{\rm tr}} = \frac{3}{32}\Big(4R_L(1+ +\cos^2\theta_{\rm tr}) + R_{\|}(2+5\sin^2\theta_{\rm tr}) + R_{\perp}(5+\cos^2\theta_{\rm tr}) - -\frac{3\pi}{2\sqrt{2}}\,A_f A_{f'}\xi_{\perp 0}\cos\theta_{\rm tr}\Big). \qquad (14)$$

The measurement of the asymmetry “up-down” relative to the plane of the decay $V_2 \to f_3 + \bar{f}_4$ for f_1-fermions created in decay (1) allows one to determine the quantity

$$-9\pi A_f A_{f'}\xi_{\perp 0}/(64\sqrt{2})$$

and thus to find the correlation coefficient $\xi_{\perp 0}$. In the absence of the interaction in the final state of the reaction, a nonzero value of this asymmetry will indicate the violation of T-invariance and also (according to the CPT-theorem) the direct violation of CP-invariance. For the decay $\Phi \to ZZ \to (e^-e^+)(\mu^-\mu^+)$, the quantities $A_e \approx A_\mu \approx 0.15$ are approximately the same [17]. Moreover, in view of the fact that the parameter $\xi_{\perp 0}$ satisfies the inequality $|\xi_{\perp 0}| \le \sqrt{R_\perp R_0} \le 1/2$, we get that the absolute value of the asymmetry “up-down” for this decay is expected to be, unfortunately, very small: it will not exceed 0.004. At the same time, the absolute value of this asymmetry for the channel $\Phi \to Z\,Z \to (c\,\bar{c})\,(b\,\bar{b})$ can be significantly greater because $A_c = 0.670$ and $A_b = 0.923$ [17] and can reach 0.10. For example, for $M = 200$ GeV and at $a = 1$, $b = 0$, and $c = i$, it is 0.04.

By studying the angular distribution over $\cos\theta_{\rm tr}$ for decay (1), we can determine the mean values of the functions $2-5\cos^2\theta_{\rm tr}$ and $5\cos^2\theta_{\rm tr}-1$ which are related to the shares of the polarizations R_L, $R_{\|}$, and $R_\perp$ of vector bosons in the following way:

$$\langle 2-5\cos^2\theta_{\rm tr}\rangle = 3R_{\|}/4 + R_\perp/4,$$

$$\langle 5\cos^2\theta_{\rm tr}-1\rangle = R_L + R_{\|}/4 + 3R_\perp/4.$$

Then if the mean values of the functions $5\cos^2\psi-1$ and $2-5\cos^2\theta_{\rm tr}$ are measured, we can determine separate values of the polarizations $R_{\|}$ and $R_\perp$ of vector bosons, namely,

$$R_\perp = 3\langle 5\cos^2\psi - 1\rangle/2 - 2\langle 2-5\cos^2\theta_{\rm tr}\rangle,$$

$$R_{\|} = -\langle 5\cos^2\psi - 1\rangle/2 + 2\langle 2-5\cos^2\theta_{\rm tr}\rangle.$$

Thus, the joint study of the one-dimensional angular distributions of process (1) over $\cos\psi$ and $\cos\theta_{\rm tr}$ in the transversity system will allow one to determine the shares of the polarizations R_L, $R_{\|}$, and $R_\perp$ of vector bosons created in the decay $\Phi \to V_1\,V_2$.

After the integration of relation (10) over $\cos\psi$ and $\cos\theta_{\rm tr}$, we obtain

$$\frac{1}{\Gamma}\frac{d\Gamma(\Phi \to V_1\,V_2 \to (f_1\bar{f}_2)\,(f_3\bar{f}_4))}{d\phi_{\rm tr}} = \frac{1}{2\pi}\times \times\Big(1+\frac{R_{\|}+3R_\perp-4R_L}{8}\cos 2\phi_{\rm tr}+\sqrt{2}\left(\frac{3\pi}{8}\right)^2 A_f A_{f'}\xi_{\|0}\times \times\sin\phi_{\rm tr}-\frac{3\pi}{8\sqrt{2}}\,A_{f'}\,\zeta_{\perp 0}\sin 2\phi_{\rm tr}-\frac{3\pi}{4}\,A_f\,\zeta_{\perp\|}\cos\phi_{\rm tr}\Big). \qquad (15)$$

It is seen that the measurement of the $\phi_{\rm tr}$-dependence of the angular distribution of the decay $H \to ZZ \to 4$ leptons can be used at LHC for the determination of the P-parity of the Higgs boson. Indeed, the azimuthal angular distribution for the decay of the pseudoscalar Higgs boson $A \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ has the form

$$\frac{1}{\Gamma}\frac{d\Gamma(A \to ZZ \to (f\bar{f})(f'\bar{f}'))}{d\phi_{\rm tr}} = \frac{1}{2\pi}\Big(1+\frac{3}{8}\cos 2\phi_{\rm tr}\Big), \qquad (16)$$

whereas, for the decay of the 0^+-state it is determined by the formula

$$\frac{1}{\Gamma}\frac{d\Gamma(H \to Z\,Z \to (f\bar{f})\,(f'\bar{f}'))}{d\phi_{\rm tr}} = \frac{1}{2\pi}\Big(1-\frac{4R_L-R_{\|}}{8}\times \times\cos 2\phi_{\rm tr} + \sqrt{2}\left(\frac{3\pi}{8}\right)^2 A_f A_{f'}\xi_{\|0}\sin\phi_{\rm tr}\Big). \qquad (17)$$

We note that, for process (2), the coefficient of $\sin\phi_{\rm tr}$ in (17) is rather small (at most 0.02). Therefore, the form of distribution (17) is defined, in fact, by the value of the quantity $4R_L - R_{\|}$. In SM, this quantity (it depends on the Higgs boson mass) can take values from 2/3 at $M \approx 2\,M_Z$ to 4 at $M \gg M_Z$.

Thus, in the transversity system at a great mass of the Higgs boson in SM, the distribution over $\phi_{\rm tr}$ depends

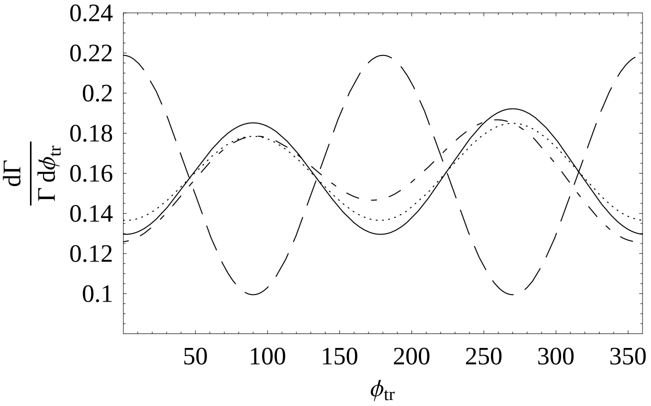

Fig. 5. Angular distribution over the azimuthal angle $\phi_{\rm tr}$ (degrees) for the process $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ in the transversity system. Solid line corresponds to SM ($a = 1$, $b = c = 0$), the dashed line - to the pure pseudoscalar state ($a = b = 0$, $c \neq 0$), and the dash-dotted and dotted lines correspond to a mixture of the CP-even and CP-odd states ($a = 1$, $b = 0$, $c = 1$) and ($a = 1$, $b = 0$, $c = i$), respectively. The mass of the Higgs boson is 200 GeV

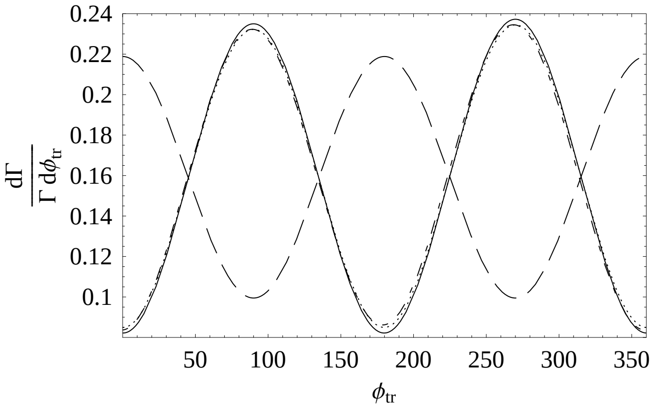

Fig. 6. The same as in Fig. 5, but for the Higgs boson mass equal to 400 GeV

significantly on the value of the azimuthal angle. We recall that, in the helicity system at a great mass of the Higgs boson in SM, the azimuthal distribution is planar [7], i.e. it does not depend on the value of the azimuthal angle in the helicity system.

Distributions (16) and (17) reveal the greatest difference in the regions, where $|\cos 2\phi_{\rm tr}| \approx 1$. Moreover, the relative difference of these distributions grows with the Higgs boson mass, which is clearly seen on the comparison of Figs. 5 and 6. In the helicity system, this difference will decrease with increase in the Higgs boson mass. Therefore, the analysis of experimental data in the transversity system can turn out to be more effective for the determination of the P-parity of the Higgs boson.

It is seen from Figs. 5 and 6 that, in the case of the violation of the CP-invariance in the decay $\Phi \to Z\,Z$, the difference between the angular distributions for the Higgs boson in SM and a boson which has no certain CP-parity depends essentially on the values of the constants a, b, and c and on the Higgs boson mass.

4. Conclusions

We have considered the possibility to study CP-properties of the Higgs boson in the decays into a pair of vector ($V_1\,V_2 = W^-\,W^+$ or $Z\,Z$) bosons which successively decay into the pairs of nonidentical fermions, $\Phi \to V_1 V_2 \to (f_1\bar{f}_2)(f_3\bar{f}_4)$. We have calculated various angular distributions for these cascade processes in the transversity system of coordinates. Moreover, as the amplitude of the decay $\Phi \to V_1\,V_2$, we have used its representation with the help of the linear-polarization states of vector bosons. The comparison of the angular distributions obtained from experimental data will allow one to measure the amplitudes of the creation of vector bosons polarized longitudinally and transversely (relative to the motion direction of bosons) and thus to establish the structure of three-boson $\Phi\,W^+W^-$- and $\Phi\,ZZ$-interactions, which is of importance for the verification of predictions of SM and for the search for the "new physics" on the TeV-scale of energies.

It is shown that the joint analysis of the one-dimensional angular distributions of process (1) over the cosine of the helicity angle ψ and the cosine of the transverse angle $\theta_{\rm tr}$ in the transversity system allows one to determine separate values of the polarization shares R_L, $R_\parallel$, and $R_\perp$ of vector bosons created in the decay $\Phi \to V_1\,V_2$. We note that the nonzero value of the polarization $R_\perp$ of vector bosons will indicate that the observed resonance is not a Higgs boson in SM.

We have also analyzed the possibility to observe effects of the violation of the CP- and T-invariances in the decay $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$. But, due to the fact that $A_e = 0.1515 \pm 0.0019$ and $A_\mu = 0.142 \pm 0.015$ [17], the relevant asymmetries for this process are insignificant. However, the situation is significantly better for the process $\Phi \to Z\,Z \to (e^-e^+)\,(b\,\bar{b})$ because $A_b = 0.923 \pm 0.020$ [17], and the asymmetry "forward-backward" $\mathcal{A}_{\rm FB}$ can attain 0.69. The measurement of this asymmetry will allow one to determine the value of the correlation coefficient $\zeta_{\perp\parallel}$. The measurement of the asymmetry "up-down" relative to the plane of the decay $Z \to f' + \bar{f}'$ for the f-fermions created in the decay $\Phi \to Z\,Z \to (f\bar{f})\,(f'\bar{f}')$ allows one to establish the value of the correlation coefficient $\xi_{\perp 0}$ which is both P-odd and $\tilde{T}$-odd. Therefore, in the absence of the final-state interaction of the reaction, a nonzero value of this coefficient will indicate the violation of the T-invariance and, according to the CPT-theorem, the direct violation of CP-invariance. Unfortunately, for the decay $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$, the absolute value of the asymmetry "up-down" will not exceed 0.004. However, for the process $\Phi \to Z\,Z \to (c\,\bar{c})\,(b\,\bar{b})$, the absolute value of this asymmetry can reach 0.1 because $A_c = 0.670 \pm 0.027$ [17]. We note that the measurement (as seen from the data presented in the Table) of the correlation coefficients between the polarization states of the Z-boson is of the basic importance in order to establish that the observed resonance is really a Higgs boson in SM.

It is shown that, in order to determine the P-parity of the Higgs boson, it is expedient to study the azimuthal distribution of the process $\Phi \to ZZ \to (e^-e^+)(\mu^-\mu^+)$ in the transversity system, because the relative difference between the distributions for 0^+- and 0^--states in this system is greater than that in the helicity system. We note that this difference becomes especially significant at great masses of the Higgs boson.

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CP-ВЛАСТИВОСТІ ХІГСІВСЬКОГО БОЗОНА
У ПРОЦЕСАХ $\Phi \to WW/ZZ \to 4$ ФЕРМІОНА
У ПОПЕРЕЧНОМУ БАЗИСІ

В.А. Ковальчук

Р е з ю м е

Досліджено прояви порушення CP-інваріантності і T-непарні кореляції за найбільш загальної ΦVV-взаємодії ($V = W^\pm$, Z) за допомогою вивчення поляризаційних ефектів у процесах $\Phi \to WW/ZZ \to 4$ ферміона у поперечному базисі. Виявлено, що для вимірювання просторової парності хігсівського бозона ефективним буде вивчення азимутального розподілу процесу $\Phi \to Z\,Z \to (e^-e^+)\,(\mu^-\mu^+)$ у поперечному базисі.