ANGULAR CORRELATIONS AND *CP* ASYMMETRIES IN THE DECAY $\Phi \to ZZ \to 4$ FERMIONS

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We investigate the possibility of detecting effects of CP violation in the process $\Phi \to ZZ \to 4$ fermions for a most general of ΦZZ coupling of a Higgs boson with a spin zero with a pair of Z bosons. Moreover, as the amplitude of the $\Phi \to ZZ$ decay we used its representation in terms of the linear polarization of the vector bosons. We have considered asymmetries that can be signal of CP violation and have estimated their sizes. It is shown, that measurement of angular correlations is important both for the test of the Standard Model, and for search of effects of new physics at the TeV scale.

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1. INTRODUCTION

The Higgs boson(s) search is one of the main tasks of present and future high-energy colliders. After the detection of the Higgs boson or several Higgs bosons, we have to probe its properties. The basic properties of any elementary particle are mass, spin, CP-parity and couplings to other particles.

In the Standard Model (SM), the physical Higgs boson H has the quantum numbers $J^{PC} = 0^{++}$. In extensions of the SM, the Higgs sector can be non-minimal, as, for instance, in the Minimal Supersymmetric Standard Model (MSSM), which contains three neutral states, two of which are CP-even h and H, and one CP-odd A, and two charged states $H^{\pm}$ [1]. While CP symmetry cannot be spontaneously broken by the tree-level MSSM Higgs potential, there is still the possibility of radiatively induced CP-violating effects in the MSSM Higgs sector, coming from explicit CP-violating phases in other sectors of the MSSM [2]. As a result, the three physical neutral Higgs bosons will not have certain CP-parity, but become mixtures of CP-even and CP-odd states. In addition, in the most general two-Higgs-doublet model (2HDM) [3], and in the simplest non-minimal supersymmetric extensions of the Standard Model (NMSSM) [4, 5], the scalar sector typically contains sources of CP-violation. Thus, determination of the CP-properties of the Higgs boson(s) will be the important point in understanding of the mechanism that breaks the electroweak symmetry and generates the masses of the known fundamental particles.

Another important problem in particle physics is the origin of the CP symmetry violation. In the SM, the violation of the CP symmetry arises due to the presence of a phase in the Cabibbo- Kobayashi-Maskawa (CKM) quark-mixing matrix [6]. The available experimental data testify that it is very likely that the CKM phase is the dominant source of the CP violation in low-energy flavor-changing processes. However, model calculations show that the CP violation present in the SM is too small to explain asymmetry between matter and antimatter in the Universe [7]. Therefore, there should be sources of the CP violation beyond the CKM mechanism. It is possible that the CP-violating effects, induced by the Higgs sector, can be directly found out only in high-energy processes in which the Higgs bosons are produced.

To study the CP-properties of the Higgs boson, it is possible to use its production characteristics and/or the energy and angular distribution of its decay products. We consider the decay of a spinless Higgs boson Φ, which may or may not be a CP eigenstate, to a pair of real Z bosons that subsequently decay into pairs of fermions (leptons or quarks),

$$\Phi \to Z\,Z \to (f_1 \bar{f}_1)\,(f_2 \bar{f}_2), \tag{1}$$

where f_1 and f_2 are distinguishable states. For CP eigenstates, a pure scalar Higgs boson will be denoted by H and a pure pseudoscalar one by A.

The cascade decay

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

is particularly important at the Large Hadron Collider (LHC) for Higgs masses $M > 2\,M_Z$, as for measurement of the Higgs boson mass, so, and for determination of its spin and P parity [8, 9, 10]. Moreover, studying of angular distributions of products of the decay (2) will allow investigating effects of possible CP violation in the $H \to Z\,Z$ decay [11, 12, 13].

The vector-vector decay $\Phi \to Z\,Z$ of a spin zero Φ boson can have orbital angular momentum L=0, 1, or 2, and three decay amplitudes govern these transitions. These amplitudes can be determined by study-

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ing the angular distributions of the final state particles. For research of the ΦZZ coupling it is the most convenient to express the decay amplitudes in terms of the linear polarization of the vector bosons. Because they are eigenstates of P-parity and their bilinear combinations have obvious physical sense: they represent polarizations or polarization correlations of the final vector bosons.

In the present paper, we consider the most general structure of the ΦZZ coupling and we give angular distributions of products of the decay (1). Comparison of these distributions with experimental data will allow to restore the structure of the ΦZZ coupling. The received results can be used also for definition of the Higgs boson P-parity and search of effects of CP violation and T-odd correlations in the $\Phi \to Z\,Z$ decay.

2. AMPLITUDES OF THE $\Phi \to Z\,Z$ DECAY

Consider the decay of a Higgs boson with a spin zero into a pair of vector bosons, and let us define our notation as $\Phi(p) \to Z(p_1,\,\epsilon_1)\,Z(p_2,\,\epsilon_2)$. We can write the most general invariant matrix element for this decay as a sum of three terms

$$A(\Phi \to Z\,Z) = a\,\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{M^2}(\epsilon_1^* \cdot p)(\epsilon_2^* \cdot p) + \\ + i\frac{c}{M^2}\varepsilon_{\mu\nu\rho\sigma}p^\mu q^\nu \epsilon_1^{*\rho}\epsilon_2^{*\sigma}, \qquad (3)$$

where M is the mass of Φ-boson and $q = p_1 - p_2$. $\varepsilon_{\mu\nu\rho\sigma}$ is totally antisymmetric tensor with $\varepsilon_{0123} = 1$. The a and b terms correspond to combinations of S- and D-wave amplitudes while the c term corresponds to the P-wave amplitude. The S- and D-states are even under the parity transformation, while the P-state is odd.

Within the SM one has $a = 1$, $b = c = 0$. For a pure pseudoscalar particle one has $c \neq 0$, $a = b = 0$. If both c and one of the other quantities are present, one cannot assign a definite P-parity to the Higgs boson.

In general the quantities a, b and c can arise from radiative loop corrections or from new physics at the TeV scale, i.e., from higher dimensional operators [14, 15]. These invariant amplitudes may be complex, and will, in general, contain both CP-conserving phases from final state interactions (e.g., between the two vector bosons) and CP-violating phases. Moreover, these quantities can receive contributions from several amplitudes, a_k, b_k, and c_k, respectively. Thus, we may write the invariant amplitudes a, b and c as

$$a = \sum_k |a_k|\,e^{i\phi_{a_k}}e^{i\delta_{a_k}},$$

$$b = \sum_k |b_k|\,e^{i\phi_{b_k}}e^{i\delta_{b_k}}, \qquad (4)$$

$$c = \sum_k |c_k|\,e^{i\phi_{c_k}}e^{i\delta_{c_k}},$$

where ϕ_{a_k}, ϕ_{b_k}, and ϕ_{c_k} are the CP-violating phases, and δ_{a_k}, δ_{b_k}, and δ_{c_k} are the CP-conserving phases. The factor i in front of the P-wave amplitude in Eq.(3) defines our convention in such a way that if all ϕ_{a_k}, ϕ_{b_k}, and ϕ_{c_k} are zero CP is conserved. Using the CPT symmetry, the matrix element for the charge conjugate decay $\bar\Phi(p) \to \bar Z(p_1,\,\epsilon_1)\,\bar Z(p_2,\,\epsilon_2)$ can be expressed as follows:

$$A(\bar\Phi \to \bar Z\,\bar Z) = \bar a\,\epsilon_1^* \cdot \epsilon_2^* + \frac{\bar b}{M^2}(\epsilon_1^* \cdot p)(\epsilon_2^* \cdot p) - \\ - i\frac{\bar c}{M^2}\varepsilon_{\mu\nu\rho\sigma}p^\mu q^\nu \epsilon_1^{*\rho}\epsilon_2^{*\sigma}, \qquad (5)$$

where the $\bar a$, $\bar b$, and $\bar c$ amplitudes can be obtained from the a, b, and c ones by changing the sign of the CP-violating phases. If CP is conserved, one has $\bar a = a$, $\bar b = b$, and $\bar c = c$. If all CP-conserving phases are zero then $\bar a = a^*$, $\bar b = b^*$, and $\bar c = c^*$.

The decay mode $\Phi \to Z\,Z$ can also be described in the transversity basis. In this basis, one decomposes the decay amplitude into components in which the polarizations of the final state vector bosons are either longitudinal (A_0), or transverse to their directions of motion and parallel ($A_\parallel$) or perpendicular ($A_\perp$) to one another. Thus, in the rest frame of $Z(p_1)$, we may write the decay amplitudes as

$$A(\Phi \to Z\,Z) = \frac{A_0}{x}\,\epsilon_1^{*L}\epsilon_2^{*L} - \frac{A_\parallel}{\sqrt{2}}\,\vec\epsilon_1^{\,*T} \cdot \vec\epsilon_2^{\,*T} - \\ - i\frac{A_\perp}{\sqrt{2}}\,\vec\epsilon_1^{\,*T} \times \vec\epsilon_2^{\,*T} \cdot \hat{\mathbf{p}}, \qquad (6)$$

and similarly for the charge conjugate decay $\bar\Phi \to \bar Z\,\bar Z$. For the charge conjugate decay the linear polarization amplitudes will be denoted $\bar A_\lambda$, where $\lambda = 0, \parallel, \perp$. $\hat{\mathbf{p}}$ is the unit vector along the direction of motion of $Z(p_2)$ in the rest of $Z(p_1)$, $\epsilon_i^{*L} \equiv \vec\epsilon_i^{\,*} \cdot \hat{\mathbf{p}}$ and $\vec\epsilon_i^{\,*T} = \vec\epsilon_i^{\,*} - \epsilon_i^{*L}\hat{\mathbf{p}}$, $i = 1,\,2$. In Eq. (6), $x \equiv \gamma^2(1+\beta^2)$, $\beta \equiv \sqrt{1 - 4\,x_Z}$ is the velocity of the Z bosons in the rest frame of Φ, $x_Z \equiv M_Z^2/M^2$, M_Z is the Z boson mass, $\gamma \equiv 1/\sqrt{1-\beta^2}$ is the Lorentz-boost factor of the Z bosons. $A_\perp$ is odd under the parity transformation, whereas A_0 and $A_\parallel$ are even. A_0, $A_\parallel$, $A_\perp$ are related to a, b and c of Eq. (3) via

$$A_0 = -\gamma^2(a\,(1+\beta^2)+b\,\beta^2),\; A_\parallel = \sqrt{2}\,a,\; A_\perp = \sqrt{2}\,\beta\,c. \qquad (7)$$

If CP is conserved in the decay $\Phi \to Z\,Z$ then $\bar A_0 = A_0$, $\bar A_\parallel = A_\parallel$, and $\bar A_\perp = -A_\perp$. If all CP-conserving phases are zero we have in this case $\bar A_0 = A_0^*$, $\bar A_\parallel = A_\parallel^*$, and $\bar A_\perp = -A_\perp^*$. We have normalized the partial widths for the three independent polarization states in such a way that

$$\Gamma(\Phi \to Z\,Z) = \frac{G_F M^3}{4\sqrt{2}\,\pi}\,x_Z^2\Big(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2\Big)\,\beta, \qquad (8)$$

where G_F is the Fermi coupling constant. Within the SM, the explicit expressions for the linear polarization amplitudes are as follows:

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

The linear polarization of the vector bosons is determined from the angular distribution of the final state decay products. In the following section we give the angular distributions of the $\Phi \to Z\,Z$ decay.

3. ANGULAR DISTRIBUTIONS OF $\Phi \to Z\,Z \to (f_1 \bar{f}_1)\,(f_2 \bar{f}_2)$

The angular distribution of products of the decay (1) can be expressed as a function of θ_1, θ_2 and ϕ angles in the helicity frame. In this frame (Fig.1), the angle $\theta_1\,(\theta_2)$ is defined as the angle between the directions of motion of $f_1\,(f_2)$ in the $Z(p_1)\,(Z(p_2))$ rest frame and the $Z(p_1)\,(Z(p_2))$ in the Φ rest frame.

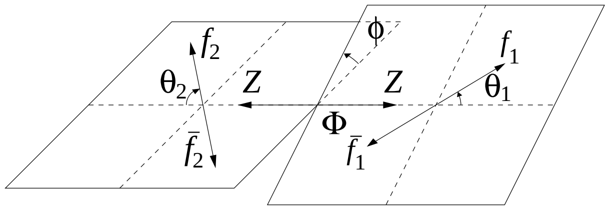

Fig.1. *Definition of helicity angles θ_1, θ_2, and ϕ, for the decay $\Phi \to Z\,Z$. The Z final states are shown in their rest frames*

The azimuthal angle ϕ is defined as the angle between the decay planes of $Z \to f_1 \bar{f}_1$ and $Z \to f_2 \bar{f}_2$ in the Φ rest frame. The decay angular distribution is:

$$\frac{1}{\Gamma}\frac{d^3\Gamma(\Phi \to Z\,Z \to (f_1\bar{f}_1)\,(f_2\bar{f}_2))}{d\cos\theta_1\,d\cos\theta_2\,d\phi} = \frac{9}{128\,\pi}\Big(4R_L\sin^2\theta_1\sin^2\theta_2 + R_{\|}\Big((1+\cos^2\theta_1)(1+\cos^2\theta_2)+ \\ +\sin^2\theta_1\sin^2\theta_2\cos 2\phi + 4A_{f_1}A_{f_2}\cos\theta_1\cos\theta_2\Big) + R_{\perp}\Big((1+\cos^2\theta_1)(1+\cos^2\theta_2)- \\ -\sin^2\theta_1\sin^2\theta_2\cos 2\phi + 4A_{f_1}A_{f_2}\cos\theta_1\cos\theta_2\Big) - 2\,\xi_{\perp\|}\sin^2\theta_1\sin^2\theta_2\sin 2\phi + 4\sqrt{2}\,(\xi_{\|0}\cos\phi- \\ -\xi_{\perp 0}\sin\phi)(A_{f_1}A_{f_2}+\cos\theta_1\cos\theta_2)\sin\theta_1\sin\theta_2 - 4\sqrt{2}\,(\zeta_{\perp 0}\cos\phi - \zeta_{\|0}\sin\phi)(A_{f_1}\cos\theta_2+ \\ +A_{f_2}\cos\theta_1)\sin\theta_1\sin\theta_2 - 4\zeta_{\perp\|}\Big(A_{f_1}(1+\cos^2\theta_2)\cos\theta_1 + A_{f_2}(1+\cos^2\theta_1)\cos\theta_2\Big)\Big), \quad (10)$$

where

$$A_{f_1} \equiv \frac{2\,g_V^{f_1}\,g_A^{f_1}}{(g_V^{f_1})^2+(g_A^{f_1})^2},\; A_{f_2} \equiv \frac{2\,g_V^{f_2}\,g_A^{f_2}}{(g_V^{f_2})^2+(g_A^{f_2})^2}.$$

The vector and axial-vector couplings are $g_V^f \equiv t_{3L}(f) - 2\,Q(f)\sin^2\theta_W$, $g_A^f \equiv t_{3L}(f)$, where $t_{3L}(f)$ is the third component of the weak isospin of fermion f, $Q(f)$ is the charge of f in units of the positron electric charge, and θ_W is the weak angle. Thus, by performing angular analysis of the decay (1), one can measure the observables R_L, $R_{\|}$, $R_{\perp}$, $\xi_{\|0}$, $\xi_{\perp 0}$, $\xi_{\perp\|}$, $\zeta_{\|0}$, $\zeta_{\perp 0}$ and $\zeta_{\perp\|}$. In terms of the linear polarization amplitudes A_0, $A_{\|}$, $A_{\perp}$, these can be expressed as follows:

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

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

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

where $i = 0, \|$.

Similarly, the angular distribution for the charge conjugate decay is simply Eq. (10), without any sign changes, but with the entire A_λ replaced by $\bar{A}_\lambda$. The expressions for the observables $\bar{R}_L$, $\bar{R}_{\|}$, $\bar{R}_{\perp}$, $\bar{\xi}_{\|0}$, $\bar{\xi}_{\perp 0}$, $\bar{\xi}_{\perp\|}$, $\bar{\zeta}_{\|0}$, $\bar{\zeta}_{\perp 0}$ and $\bar{\zeta}_{\perp\|}$ are similar to those given in Eq. (11), with the replacement $A_\lambda \to \bar{A}_\lambda$.

Now consider what is necessary to observe the *CP* violation. There are three sorts of observables in which one might observe the *CP* violation: (i) the partial rates, Γ and $\bar{\Gamma}$, (ii) the *CP*-even observables, namely R_L, $R_{\|}$, $R_{\perp}$, $\xi_{\|0}$, and $\zeta_{\|0}$, (iii) the *CP*-odd observables, namely $\xi_{\perp 0}$, $\xi_{\perp\|}$, $\zeta_{\perp 0}$, and $\zeta_{\perp\|}$. If *CP* is conserved in the $\Phi \to Z\,Z$ decay then these observable quantities should satisfy to following conditions:

$$\Gamma(\Phi \to Z\,Z) = \bar{\Gamma}(\bar{\Phi} \to \bar{Z}\,\bar{Z}), \quad (12)$$

$$\bar{R}_L = R_L,\; \bar{R}_{\|} = R_{\|},\; \bar{R}_{\perp} = R_{\perp},\; \bar{\xi}_{\|0} = \xi_{\|0},\; \bar{\zeta}_{\|0} = \zeta_{\|0}, \quad (13)$$

$$\bar{\xi}_{\perp 0} = -\xi_{\perp 0},\; \bar{\xi}_{\perp\|} = -\xi_{\perp\|}, \bar{\zeta}_{\perp 0} = -\zeta_{\perp 0},\; \bar{\zeta}_{\perp\|} = -\zeta_{\perp\|}. \quad (14)$$

Any deviation from these conditions is a manifestation of the *CP* violation. Note that if, in Eq. (4), all *CP*-violating phases have the same values then conditions (12)–(14) will be carried out also. On the other hand, if, in Eq. (4), all *CP*-conserving phases will have the same values or zero ones then

$$\bar{R}_L = R_L, \bar{R}_{\|} = R_{\|}, \bar{R}_{\perp} = R_{\perp}, \bar{\xi}_{\|0} = \xi_{\|0}, \bar{\zeta}_{\|0} = -\zeta_{\|0}, \quad (15)$$

$$\bar{\xi}_{\perp 0} = \xi_{\perp 0},\; \bar{\xi}_{\perp\|} = \xi_{\perp\|}, \bar{\zeta}_{\perp 0} = -\zeta_{\perp 0},\; \bar{\zeta}_{\perp\|} = -\zeta_{\perp\|}, \quad (16)$$

and the only signals of *CP* violation are $\xi_{\perp 0}$, $\xi_{\perp\|}$, and $\zeta_{\|0}$. In fact, in the absence of final state interactions a non-zero value of $\zeta_{\|0}$ or $\xi_{\perp i}$ by itself is a signal of time reversal violation. Thus, if, in Eq. (4), two or more *CP*-violating phases will have different values, and some of the *CP*-conserving phases will have non-zero values, only in this case one can observe *CP* violation in all of the observables.

After discovery of the Higgs boson, it will be necessary to investigate structure of the $\Phi Z Z$ coupling. Now we consider what information on the $\Phi Z Z$ coupling structure can be extracted from one-dimensional angular distributions of the process (1).

Integrating (10) over the variables $\cos\theta_2$, and ϕ, we obtain

$$\frac{1}{\Gamma}\frac{d\Gamma(\Phi\to ZZ\to(f_1\bar{f}_1)\,(f_2\bar{f}_2))}{d\cos\theta_1}=\frac{3}{8}\Big(2R_L\sin^2\theta_1+$$

$$+(R_\parallel+R_\perp)(1+\cos^2\theta_1)-4A_{f_1}\zeta_{\perp\parallel}\cos\theta_1\Big). \quad (17)$$

Similar distribution takes place on the $\cos\theta_2$ with obvious replacements in Eq. (17) $\theta_1\to\theta_2$ and $A_{f_1}\to A_{f_2}$.

Fractions of longitudinal and transverse polarizations of the Z boson in the $\Phi\to Z\,Z$ decay can be measured if to compare the angular distribution (17) to the experimental data (using the method of maximum likelihood) or having measured mean values of functions $2-5\cos^2\theta_1$ and $5\cos^2\theta_1-1$, which are $\langle 2-5\cos^2\theta_1\rangle=R_L$ and $\langle 5\cos^2\theta_1-1\rangle=R_\parallel+R_\perp$ (note that $\langle\cos\theta_1\rangle=-A_f\,\zeta_{\perp\parallel}$).

The forward-backward asymmetry in the $f_1\bar{f}_1$ system, defined as

$$\mathcal{A}_{FB}\equiv\frac{\mathcal{F}-\mathcal{B}}{\mathcal{F}+\mathcal{B}},\ \mathcal{F}\equiv\int_0^1\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1}\,d\cos\theta_1,$$

$$\mathcal{B}\equiv\int_{-1}^0\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1}\,d\cos\theta_1, \quad (18)$$

is $-3A_{f_1}\,\zeta_{\perp\parallel}/2$. Therefore, the measurement of this asymmetry will allow to define the size of the parameter $\zeta_{\perp\parallel}$. The absolute size of the asymmetry will not exceed 0.11 for the decay $\Phi\to Z\,Z\to(e^-e^+)\,(\mu^-\mu^+)$. Since $A_e=0.1515\pm0.0019$ [16] and $|\zeta_{\perp\parallel}|\le\sqrt{R_\perp R_\parallel}\le 1/2$. For other channels of the decay, it can be much more. So, for the decay $\Phi\to Z\,Z\to(b\,\bar{b})\,(\mu^-\mu^+)$ it can reach 0.69. Since $A_b=0.923\pm0.020$ [16]. So, for example, for $M=200\,GeV$ and at $a=c=1$ and $b=0$, this asymmetry will be equal: $\mathcal{A}_{FB}(\Phi\to ZZ\to(b\,\bar{b})(\mu^-\mu^+))=-0.26$ ($\mathcal{A}_{FB}(\Phi\to ZZ\to(e^-e^+)(\mu^-\mu^+))=-0.04$).

Note that the parity of the Higgs boson can be measured by dividing the events into two bins, with $|\cos\theta_1|<1/2$ and $|\cos\theta_1|>1/2$, denoted by $\mathcal{E}$ (equatorial) and $\mathcal{P}$ (polar) respectively:

$$\mathcal{E}\equiv\int_{-1/2}^{1/2}d\cos\theta_1\,\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1},$$

$$\mathcal{P}\equiv\left(\int_{-1}^{-1/2}d\cos\theta_1+\int_{1/2}^{1}d\cos\theta_1\right)\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1},$$

$$\mathcal{E}-\mathcal{P}=3(3\,R_L-1)/16.$$

The dependence of $\mathcal{E}-\mathcal{P}$ on the Higgs mass is shown in Fig.2. The pseudoscalar shows the largest deviation from the SM Higgs.

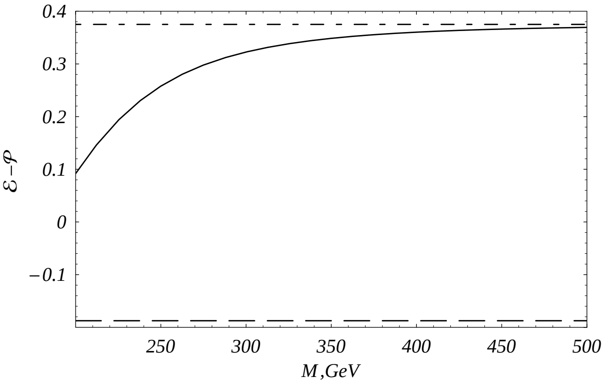

Fig.2. *The variation of $\mathcal{E}-\mathcal{P}$ with the Higgs mass. The solid curve shows the SM case ($a=1$, $b=c=0$) while the dashed curve is for a pure* CP*-odd state ($a=b=0$, $c\neq0$). The dot-dashed curve is for a* CP*-even state ($a=c=0$, $b\neq0$)*

It would have $\mathcal{E}-\mathcal{P}=-3/16$ whereas the SM Higgs always has $\mathcal{E}-\mathcal{P}>0$.

Finally, the distribution in the angle ϕ between the decay planes, after integration over other variables, takes the simple form

$$\frac{1}{\Gamma}\frac{d\Gamma(\Phi\to Z\,Z\to(f_1\bar{f}_1)\,(f_2\bar{f}_2))}{d\phi}=\frac{1}{2\,\pi}\Big(1+$$

$$+\frac{R_\parallel-R_\perp}{4}\cos2\phi-\frac{\xi_{\perp\parallel}}{2}\sin2\phi+$$

$$+\sqrt{2}\left(\frac{3\pi}{8}\right)^2A_{f_1}A_{f_2}(\xi_{\parallel0}\cos\phi-\xi_{\perp0}\sin\phi)\Big). \quad (19)$$

Nonvanishing $\xi_{\perp0}$ and/or $\xi_{\perp\parallel}$ are indications of the *CP* nonconservation. Measurement these $\sin\phi$ or $\sin2\phi$ dependences in the event distribution will establish the *CP* nonconservation. For research of the *CP* violation effects in the $\Phi\to ZZ$ decay, it is necessary to define the number of the events of the process (1) got in each of four quadrants

$$N_j\equiv\int_{\pi(j-1)/2}^{\pi j/2}d\phi\,\frac{1}{\Gamma}\frac{d\Gamma}{d\phi},$$

where $j=1,2,3,4$ and to measure asymmetries

$$\mathcal{A}_1\equiv\frac{N_1+N_2-N_3-N_4}{N_1+N_2+N_3+N_4} \quad (20)$$

and

$$\mathcal{A}_2\equiv\frac{N_1-N_2+N_3-N_4}{N_1+N_2+N_3+N_4}. \quad (21)$$

These asymmetries are equal to $\mathcal{A}_1=-9\pi A_{f_1}A_{f_2}\xi_{\perp0}/(16\sqrt{2})$ and $\mathcal{A}_2=-\xi_{\perp\parallel}/\pi$.

For the decay $\Phi\to ZZ\to(e^-e^+)(\mu^-\mu^+)$, the absolute size of the asymmetry $\mathcal{A}_1$ is expected small, it should not exceed 0.01. Since $A_e=0.1515\pm0.0019$, $A_\mu=0.142\pm0.015$ [16] and $|\xi_{\perp0}|\le\sqrt{R_\perp R_0}\le1/2$. For other channels of the decay, it can be much more. So, for the decay $\Phi\to Z\,Z\to(c\,\bar{c})\,(b\,\bar{b})$ it can reach 0.39. Since $A_c=0.670\pm0.027$, $A_b=0.923\pm0.020$ [16]. So, for example, for $M=200$ GeV and at $a=1$, $b=0$ and $c=i$, this asymmetry will be equal to $\mathcal{A}_1(\Phi\to ZZ\to(c\,\bar{c})\,(b\,\bar{b}))=0.15$.

Note that value of the asymmetry $\mathcal{A}_2$ does not depend on the Z bosons decay channel. Absolute size of this asymmetry can reach 0.16. So, for example, for $M = 200$ GeV and at $a = 1$, $b = 0$ and $c = i$ it will be -0.06.

4. CONCLUSIONS

We investigated the effects of the CP violation and T-odd correlations for the most general structure of the ΦZZ coupling of a Higgs boson with a spin zero with a pair of real Z bosons. We have calculated various angular distributions of cascade process of the decay $\Phi \to ZZ \to 4\,$fermions. Moreover, as the amplitude of the decay $\Phi \to ZZ$ we used its representation in terms of the linear polarization of the vector bosons. Comparison of the obtained distributions with experimental data will allow to measure amplitudes of the Z bosons production in which the polarizations of the final state vector bosons are either longitudinal, or transverse to their directions of motion and parallel or perpendicular to one another and, thus, to establish the structure of the ΦZZ coupling.

We have also analyzed the possibility of detecting the T-odd correlations and the effects of the CP symmetry violation in the decays $\Phi \to Z\,Z \to (e^- e^+)\;(\mu^- \mu^+)$, $\Phi \to Z\,Z \to (b\,\bar{b})\;(\mu^- \mu^+)$ and $\Phi \to Z\,Z \to (c\,\bar{c})\;(b\,\bar{b})$. It has been shown that the forward-backward asymmetry for the process $\Phi \to Z\,Z \to (b\,\bar{b})\;(\mu^- \mu^+)$ can reach 0.69. Note that measurement of this asymmetry will allow to fix the size of the correlation coefficient $\zeta_{\perp\parallel}$. Measurement of the CP asymmetry of the process $\Phi \to Z\,Z \to (c\,\bar{c})\;(b\,\bar{b})$, which can reach 0.38, will allow to define the size of the correlation coefficient $\xi_{\perp 0}$. A non-zero value of this coefficient will testify the T violation in the $\Phi \to ZZ$ decay in the absence of the final state interactions. Clearly, the measurement of polarization correlations of the final vector bosons will be important both for the test of the SM predictions , and for search of the effects of new physics at the TeV scale.

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УГЛОВЫЕ КОРРЕЛЯЦИИ И *CP*-АСИММЕТРИИ В РАСПАДЕ $\Phi \to ZZ \to 4$ ФЕРМИОНА

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Мы исследуем возможность обнаружения эффектов CP-нарушения в процессе $\Phi \to ZZ \to 4$ фермиона для самого общего ΦZZ-взаимодействия хиггсовского бозона с нулевым спином с парой Z-бозонов. Причем, в качестве амплитуды распада $\Phi \to ZZ$ мы использовали её представление посредством линейно поляризационных состояний векторных бозонов. Мы рассмотрели асимметрии, которые могут быть сигналом CP-нарушения и оценили их величины. Показано, что измерение угловых корреляций является важным как для проверки предсказаний стандартной модели, так и для поиска эффектов "новой физики"в ТэВ-м масштабе.

КУТОВІ КОРЕЛЯЦІЇ ТА *CP*-АСИМЕТРІЇ У РОЗПАДУ $\Phi \to ZZ \to 4$ ФЕРМІОНА

В.А. Ковальчук

Ми досліджуємо можливість виявлення ефектів CP-порушення у процесі $\Phi \to ZZ \to 4$ ферміона для найбільш загальної ΦZZ-взаємодії хігсівського бозона з нульовим спіном з парою Z-бозонів. Причому, у якості амплітуди розпаду $\Phi \to ZZ$ ми використали її подання за допомогою лінійно поляризаційних станів векторних бозонів. Ми розглянули асиметрії, які можуть бути сигналом CP-порушення та оцінили їхні величини. Показано, що вимір кутових кореляцій є важливим як для перевірки передбачень стандартної моделі, так і для пошуку ефектів "нової фізики"в ТеВ-му масштабі.