HIGGS BOSON DECAY TO γZ AND TEST OF CP AND CPT SYMMETRIES*

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Polarization characteristics of γZ state in the Higgs boson decay $h \to \gamma Z$ are discussed. Based on the effective Lagrangian, describing $h\gamma Z$ interaction with CP-even and CP-odd parts, we calculate the polarization parameters ξ_1, ξ_2, ξ_3. A nonzero value of the photon circular polarization, defined by the parameter ξ_2, arises due to the presence of both parts in the effective Lagrangian and its non-Hermiticity. A measurement of the circular polarization through the forward–backward asymmetry of fermions in the decay $h \to \gamma\, Z \to \gamma\, f\, \bar{f}$ will allow one to search for deviation from the Standard Model and a possible violation of the CPT symmetry.

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1. Introduction

The ATLAS and CMS collaborations at the LHC have recently observed [1, 2] a boson h with mass around 126 GeV with the statistical significance of about five standard deviations. The experimental evidence of this new particle is the strongest in the two-photon and four-lepton final channels, where the detectors give the best mass resolution.

Although the decay pattern of h is mainly consistent with the predictions of the Standard Model (SM), the clarification of the nature of this particle still needs more data and time. The spin of this boson is known to be zero or two, while the CP properties are not yet ascertained. Recent data are more consistent with the pure scalar boson hypothesis than the pure pseudoscalar one [3]. Though in the SM the Higgs boson has $J^{\mathrm{PC}} = 0^{++}$, there are many extensions of the SM with a more complicated Higgs sector, in which some of the Higgs bosons may not have the definite CP parity [4].

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Recently, the CP properties of the Higgs boson in the two-photon decay channel $h \to \gamma\gamma$ have been addressed in Ref. [5]. In Ref. [6] a model-independent analysis of the CP violation effects in the Higgs boson into a pair of the gauge bosons W^+, W^- or Z, Z has been presented. The author has studied the angular distributions of the fermions $f = \ell, q$ in the cascade processes $h \to V_1 V_2 \to (f_1 \bar{f}_2)(f_3 \bar{f}_4)$ and analyzed possibilities of observation of the CP violation in these decays to various final lepton and quark pairs.

Here, we suggest to study CP and possible CPT violation in the decay

$$h \to \gamma Z \to \gamma f \bar{f} \tag{1}$$

with $f = \ell, q$. It turns out that the decay distribution over the angle θ between the momentum of the fermion f (in the rest frame of the Z) and momentum of the Z (in the rest frame of the h) gives information on the photon circular polarization which can be measured through the forward–backward asymmetry $A_{\rm FB}$ [7].

In the SM, the $h \to \gamma Z$ decay amplitude in the lowest order is determined by the loop contributions [8] which have a small but nonzero imaginary part arising due to rescattering effects $h \to f\bar{f} \to \gamma Z$ for the fermions f with masses $m_f \leq m_h/2$. The corresponding effective Lagrangian $\mathcal{L}_{\rm eff}^{h\gamma Z}$, describing interaction of h, γ and Z, is thus non-Hermitian. Non-Hermiticity of the effective Lagrangian leads to a nonzero value of the net photon helicity, once we assume a mixture of the CP violating term in $\mathcal{L}_{\rm eff}^{h\gamma Z}$. Note that in the SM and theories beyond the SM which are CPT symmetric, there are no sources of non-Hermiticity of $\mathcal{L}_{\rm eff}^{h\gamma Z}$ apart from rescattering effects.

The CPT theorem is one of the most profound results of quantum field theory [9]. It is a consequence of Lorentz invariance, locality, connection between spin and statistics, and a Hermitian Hamiltonian. However, there are many extensions of the SM in which the CPT violation appears due to nonlocality in the string theory, or violation of the Lorentz symmetry in the extra dimensional models (see, for example, [10]). One can also mention possible deviations from the standard quantum mechanical evolution of states in some models of quantum gravity, and the corresponding breakdown of the CPT symmetry is investigated in the neutral-meson system, where novel CPT-violating observables for the ϕ-factories and B-factories are proposed [11]. The CPT violating effects in some of these underlying theories, in principle, can be additional sources of non-Hermiticity of the effective Lagrangian $\mathcal{L}_{\rm eff}^{h\gamma Z}$ and hence contribute to the photon circular polarization.

As for experimental results on the SM Higgs boson decay to the Z boson and photon, we mention recent ATLAS and CMS results [12, 13]. The Higgs production cross section times the $h \to \gamma Z$ branching fraction limits are about an order of magnitude larger than the SM expectation for $m_h = 125$ GeV.

2. Formalism

The effective Lagrangian for the $h\gamma Z$ interaction can be written, as

$$\mathcal{L}_{\rm eff}^{h\gamma Z} = \frac{e\,g}{16\,\pi^2\,v}\Big(c_{1Z}\,Z_{\mu\nu}F^{\mu\nu}h - c_{2Z}\,(\partial_\mu h\,Z_\nu - \partial_\nu h\,Z_\mu)\,F^{\mu\nu} - \tilde{c}_Z\,Z_{\mu\nu}\widetilde{F}^{\mu\nu}h\Big)\,, \tag{2}$$

where e is the positron electric charge, g is the $\mathrm{SU}(2)_{\rm L}$ coupling constant and $v = \left(\sqrt{2}G_{\rm F}\right)^{-1/2} \approx 246$ GeV is the vacuum expectation value of the Higgs field. Here, $F_{\mu\nu}$ and $Z_{\mu\nu}$ are the standard field strengths for the electromagnetic and Z field and $\widetilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}/2$, with convention $\varepsilon_{0123} = +1$. Dimensionless parameters c_{1Z}, c_{2Z} and $\tilde{c}_Z$ are effective coupling constants. As these coupling constants are, in general, complex-valued, the operator (2) is non-Hermitian, while being local and Lorentz invariant.

It is convenient to write the coupling c_{1Z} as the sum of terms in the SM and new physics (NP) beyond the SM: $c_{1Z} = c_Z^{\rm SM} + c_{1Z}^{\rm NP}$. In the SM, $c_{2Z} = \tilde{c}_Z = 0$ and their nonzero values come from effects of NP. The coupling $c_Z^{\rm SM}$ has a small imaginary part which arises due to the intermediate on mass shell $\ell^+\,\ell^-$ and $q\bar{q}$ states in the one-loop contributions [where $\ell = e,\ \mu,\ \tau$ denote leptons and $q = u,\ d,\ s,\ c,\ b$ denote quarks (excluding t quark)]. We calculate coupling $c_Z^{\rm SM}$ in the one-loop order [8, 14] and obtain [7]

$$c_Z^{\rm SM} = -5.540 + 0.005i\,, \tag{3}$$

where for $m_h = 126$ GeV the SM parameters are taken from [15] and the quark masses — from [16].

The terms proportional to c_{1Z} and c_{2Z} above correspond to a CP-even scalar h, while the term proportional to $\tilde{c}_Z$ indicates a CP-odd pseudoscalar h. The presence of both sets of terms means that h is not a CP eigenstate. Interference of these terms leads to CP violating effects which reveal in polarization states of the photon.

Values of coupling constants $c_{1Z}^{\rm NP}$, c_{2Z}, $\tilde{c}_Z$ can be calculated in various models. In particular, there are models with more than one Higgs doublet which induce the CP violation due to the specific coupling of neutral Higgs bosons to fermions. We calculate $c_{1Z}^{\rm NP}$, c_{2Z}, $\tilde{c}_Z$ assuming that the couplings of h boson to the fermion fields, ψ_f, are given by the Lagrangian including both scalar and pseudoscalar parts

$$\mathcal{L}^{hff} = -\sum_f \frac{m_f}{v}\, h\, \bar{\psi}_f \, (1 + s_f + i\, p_f \gamma_5)\, \psi_f \,, \tag{4}$$

where m_f is the fermion mass, s_f, p_f are real parameters and $s_f = p_f = 0$ corresponds to the SM.

Evaluating the fermion contribution to the one-loop $h \to \gamma\, Z$ amplitude, we obtain (see details in Ref. [7])

$$\begin{aligned} c_{1Z}^{\rm NP} &\approx 0.3253 s_t - (8.2 s_b + 1.2 s_c + 0.2 s_\tau) \times 10^{-3} \\ &\quad + i\,(4.8 s_b + 0.5 s_c + 0.1 s_\tau) \times 10^{-3} \,, \\ \tilde{c}_Z &\approx -0.4939 p_t + (9.6 p_b + 1.3 p_c + 0.3 p_\tau) \times 10^{-3} \\ &\quad - i\,(4.9 p_b + 0.5 p_c + 0.1 p_\tau) \times 10^{-3} \,. \end{aligned} \tag{5}$$

In obtaining numerical values in (5), we have taken into account dominant contributions from the charm, bottom, top quarks and τ lepton, in particular, the charm, bottom quarks and τ lepton give rise to the imaginary parts of the couplings in (5).

In terms of the parameters s_f and p_f, the width of the decay $h \to f \bar{f}$ is written as

$$\mathit{\Gamma}\left(h \to f \bar{f}\,\right) = \frac{N_f G_{\rm F}}{4\sqrt{2}\pi}\, m_f^2\, m_h\, \beta_f \left((1 + s_f)^2 \beta_f^2 + p_f^2\right) \,, \tag{6}$$

where m_h is the mass of h boson, $\beta_f = \sqrt{1 - 4 m_f^2 / m_h^2}$, and $N_f = 1\,(3)$ for leptons (quarks). With a good accuracy one can put $\beta_f = 1$. Note that if one chooses $(1 + s_f)^2 + p_f^2 = 1$, then the width in Eq. (6) coincides with the decay width of the SM Higgs boson.

3. Amplitudes and angular distributions

We consider the decay of the zero-spin Higgs h boson into γ and Z boson

$$h(p) \to \gamma(k_1, \epsilon_1)\, Z(k_2, \epsilon_2) \,, \tag{7}$$

where $k_1\,(k_2)$ is the four-momentum of photon (Z boson), $\epsilon_1\,(\epsilon_2)$ is the polarization vector of the photon (Z boson).

The helicity amplitudes for the decay (7) are

$$H_\pm = -\frac{e g m_h^2}{16\, \pi^2\, v} \left(1 - \frac{m_Z^2}{m_h^2}\right) (c_{1Z} + c_{2Z} \pm i\, \tilde{c}_Z) \,, \tag{8}$$

with the decay width

$$\Gamma(h\to\gamma Z) = \frac{1}{16\,\pi m_h}\left(1-\frac{m_Z^2}{m_h^2}\right)\left(|H_+|^2+|H_-|^2\right) , \tag{9}$$

where m_Z is the Z boson mass.

From helicity amplitudes, we find the polarization parameters

$$\begin{aligned}
\xi_1 &= \frac{2\,\mathrm{Im}\left(H_+H_-^*\right)}{|H_+|^2+|H_-|^2} = \frac{2\,\mathrm{Re}((c_{1Z}+c_{2Z})\tilde{c}_Z^*)}{|c_{1Z}+c_{2Z}|^2+|\tilde{c}_Z|^2} , \\
\xi_2 &= \frac{|H_+|^2-|H_-|^2}{|H_+|^2+|H_-|^2} = \frac{2\,\mathrm{Im}((c_{1Z}+c_{2Z})\tilde{c}_Z^*)}{|c_{1Z}+c_{2Z}|^2+|\tilde{c}_Z|^2} , \\
\xi_3 &= -\frac{2\,\mathrm{Re}\left(H_+H_-^*\right)}{|H_+|^2+|H_-|^2} = \frac{|\tilde{c}_Z|^2-|c_{1Z}+c_{2Z}|^2}{|c_{1Z}+c_{2Z}|^2+|\tilde{c}_Z|^2} .
\end{aligned} \tag{10}$$

In the decay (7), due to the zero-spin nature of the Higgs boson, the photon and Z boson have equal helicities[1]. This allows for measurement of the photon circular polarization, described by the parameter ξ_2, in the decay $h\to\gamma\,Z\to\gamma\,f\bar{f}$. Indeed, we derive for this process the following angular distribution in the polar angle θ between the momentum of the fermion f in the Z boson rest frame and the direction of the Z boson motion in the h boson rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma\left(h\to\gamma\,Z\to\gamma\,f\bar{f}\right)}{d\cos\theta} = \frac{3}{8}\left(1+\cos^2\theta-2\,A^{(f)}\,\xi_2\,\cos\theta\right) , \tag{11}$$

$$A^{(f)} \equiv 2\,g_{\mathrm{V}}^f g_{\mathrm{A}}^f\left(\left(g_{\mathrm{V}}^f\right)^2+\left(g_{\mathrm{A}}^f\right)^2\right)^{-1} \tag{12}$$

with vector, g_{V}^f, and axial-vector, g_{A}^f, constants defined in [15] (ch. 10.1).

Measurement of the forward–backward asymmetry A_{FB} relative to the direction of Z boson motion in the h boson rest frame for the f fermions produced in decay (1)

$$A_{\mathrm{FB}} \equiv \frac{F-B}{F+B} = -\frac{3}{4}\,A^{(f)}\,\xi_2 , \tag{13}$$

$$F \equiv \int\limits_0^1 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}\,d\cos\theta , \qquad B \equiv \int\limits_{-1}^0 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}\,d\cos\theta \tag{14}$$

allows one to find polarization parameter ξ_2.

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[1] Of course, for background processes the photon and Z boson helicities can differ.

Consider now feasibility to measure the distribution (12) at the LHC after its upgrade to higher luminosity and energy $\sqrt{s} = 14$ TeV. Taking into account various mechanisms of the Higgs boson production in pp collisions, the inclusive cross section is $\sigma = 57.0163$ pb [16]. Then the cross section for the process $p\,p \to h\,X \to \gamma\,Z\,X \to \gamma\,\ell^+\ell^-\,X$ in the SM is

$$\sigma \times \mathrm{BR}(h \to \gamma Z)\,\mathrm{BR}(Z \to \ell^+\ell^-) = 6.24 \text{ fb}\,, \tag{15}$$

where $\ell = e$, μ and the branching fractions are taken from Refs. [15, 17]. In order to observe the forward–backward asymmetry A_{FB} for maximal value $|\xi_2| = 1$ at a $3\,\sigma$ level, the number of events should be bigger than 734. This number of events can be obtained, with ideal detector, with integrated luminosity about 120 fb^{-1}.

4. Results of calculation and discussion

First, we note that in the SM the polarization parameters are $\xi_1^{\mathrm{SM}} = \xi_2^{\mathrm{SM}} = 0$ and $\xi_3^{\mathrm{SM}} = -1$. Any deviations of the measured values of ξ_i from ξ_i^{SM} $(i = 1, 2, 3)$ will indicate presence of effects beyond the SM.

In order to estimate magnitude of effects of NP, we consider the model (4) with the scalar and pseudoscalar couplings of fermions to the Higgs boson. We choose the parameters

$$p_t = p_b = p_c = p_\tau = \pm\,1/\sqrt{2}\,, \qquad s_t = s_b = s_c = s_\tau = 1/\sqrt{2} - 1 \tag{16}$$

satisfying normalization $(1 + s_f)^2 + p_f^2 = 1$ discussed in Sec. 2.

As a result, for the decay $h \to \gamma\,Z$, we find

$$\begin{aligned} \xi_1 &= \pm 0.121\,, \qquad \xi_2 = \mp 0.001\,, \qquad \xi_3 = -0.993\,, \\ \mu_{\gamma Z} &\equiv \frac{\Gamma(h \to \gamma\,Z)}{\Gamma^{\mathrm{SM}}(h \to \gamma\,Z)} = 1.04\,. \end{aligned} \tag{17}$$

In addition, the $h \to f\bar{f}$ decay width calculated with s_f, p_f in (16) coincides with the SM decay width and agrees with the CMS data [18] for $h \to \tau^+\tau^-$ and $h \to b\,\bar{b}$ decays.

Thus the rescattering effects on the one-loop level result in values of ξ_2 in the $h \to \gamma Z$ decay about 10^{-3}. It would be of interest to check in the experimental analysis of the distribution (12) whether the parameter ξ_2 is very small indeed. If the analysis yielded sizable values of ξ_2, this would mean the presence of additional sources of non-Hermiticity of the effective Lagrangian. The latter may arise, for example, due to the breaking of Hermiticity in an underlying (fundamental) theory at very small distances. Since the requirement of Hermiticity is one of the conditions in the proof of the CPT theorem [9], the measurement of the photon circular polarization in the decay $h \to \gamma Z \to \gamma \bar{f} f$ through the forward–backward asymmetry A_{FB} can be useful for testing the CPT symmetry.

The parameters ξ_1 and ξ_3 carry information on the CP properties of the Higgs boson. Besides, ξ_1 is CP-odd and T-odd observable and, in the absence of final-state interaction between the leptons and fermions, a nonzero value of ξ_1 will point to the violation of T invariance.

5. Conclusions

The polarization properties of the γZ state in the decay $h \to \gamma Z$ of recently discovered scalar boson have been considered. We have chosen the effective Lagrangian, describing $h\gamma Z$ interaction with CP-even and CP-odd parts. This allowed for calculation of polarization parameters ξ_1, ξ_2, ξ_3. In the SM, these parameters take on values $\xi_1^{\mathrm{SM}} = \xi_2^{\mathrm{SM}} = 0$, $\xi_3^{\mathrm{SM}} = -1$ and deviations of the measured values of ξ_i from ξ_i^{SM} $(i = 1, 2, 3)$ will point to effects of NP.

The parameter ξ_2, which defines the circular polarization of the photon, can be measured in the $h \to \gamma Z \to \gamma f \bar{f}$ decay through the forward–backward asymmetry $A_{\mathrm{FB}} \sim \xi_2$ of the fermion f. The parameters ξ_1, ξ_3, which define the correlation of linear polarizations of γ and Z, can be extracted from the azimuthal angle distribution in the process $h \to \gamma^* Z \to \ell^+\ell^- Z$ with decay $Z \to \bar{f} f$ on the mass shell (see Ref. [7]).

In numerical estimates of these parameters, we included the one-loop contribution from the SM, and models beyond the SM. Namely, we used the model (4) with the scalar and pseudoscalar couplings of fermions to the Higgs boson on the one-loop level. In addition, in Ref. [7] we applied effective field-theory approach [19] in which NP is described by gauge invariant dimension-6 operators in the fields of the SM.

The value of photon circular polarization turns out to be very small, of the order of 10^{-3}. In general, nonzero value of ξ_2 arises due to the presence of the CP-even and CP-odd parts in the effective Lagrangian $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$ and absorptive parts of one-loop diagrams, or rescattering effects of the type $h \to a\bar{a} \to \gamma Z$, where a are charged particles with masses $m_a \leq m_h/2$. Only leptons and quarks u, d, s, c, b satisfy this condition and hence contribute to absorptive parts of one-loop diagrams. Contributions from leptons e, μ and light quarks u, d, s are negligibly small. The couplings of h to the τ lepton and bottom quark are constrained by the CMS data on $h \to \tau^+\tau^-$ and $h \to b\bar{b}$ decays.

Apart from rescattering effects, in the framework of CPT symmetric models, there are no sources of non-Hermiticity of $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$ which could contribute to parameter ξ_2. If there is a violation of the CPT symmetry in an underlying theory at small distances, then this may give rise to additional non-Hermiticity effects in $\mathcal{L}_{\rm eff}^{h\gamma Z}$ which will change the value of ξ_2. Therefore, the measurement of this parameter in the $h \to \gamma\, Z \ \to \gamma\, f\, \bar{f}$ process would allow one to test the prediction of the SM, and to search for deviations from the SM, and even possible effects of the CPT violation in an underlying theory.

Nonzero values of parameter ξ_1 point to the violation of CP symmetry in the $h \to \gamma Z$ decay. In the chosen models of NP, ξ_1 appears to be 0.1–0.2. Its experimental determination can put constraints on models describing physics beyond the SM.

In conclusion, we hope that with increasing the integrated luminosity at the LHC the investigation of this process will become possible.

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