Polarization effects in the Higgs boson decay to γZ and test of CP and CPT symmetries

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Polarization characteristics of $\gamma\gamma$ and γZ states in the Higgs boson decays $h \to \gamma\gamma$ and $h \to \gamma Z$ are discussed. Based on effective Lagrangian, describing $h\gamma\gamma$ and $h\gamma Z$ interactions with CP-even and CP-odd parts, we calculate polarization parameters ξ_1, ξ_2, ξ_3. A nonzero value of the photon circular polarization, defined by parameter ξ_2, arises due to presence of both parts in effective Lagrangian and its non-Hermiticity. The circular polarization is proportional to the forward-backward asymmetry of fermions in the decay $h \to \gamma Z \to \gamma f\bar{f}$. Measurement of this observable would allow one to search for deviation from the standard model and possible violation of CPT symmetry. We discuss also a possibility to measure parameters ξ_1, ξ_3, describing correlation of linear polarizations of photon and Z boson, in the decay $h \to \gamma^* Z \to \ell^+\ell^- Z$ via distribution over the azimuthal angle between the decay planes of $\gamma^* \to \ell^+\ell^-$ and $Z \to \bar{f}f$. Deviation of the measured value of ξ_1 from zero will indicate CP violation in the Higgs sector.

I. INTRODUCTION

The ATLAS and CMS collaborations at the LHC have recently observed [1,2] a boson h with mass around 126 GeV with 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 $J^{PC} = 0^{++}$, there are many extensions of the SM with a more complicated Higgs sector, in which some of the Higgs bosons may not have definite CP parity [4–6].

This aspect of the Higgs study is also related to the origin of the CP violation. In the SM the source of the CP violation is the complex irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [7], however this effect is not sufficient to explain the observed matter-antimatter asymmetry in the Universe [8]. There may be other mechanisms of the CP violation beyond the CKM matrix, for example, in the Higgs sector. From this point of view, the elucidation of the CP properties of the observed h boson would be an important step towards clarification of the mechanisms giving rise to the masses of particles, their mixing and CP violation.

Recently the CP properties of the Higgs boson in the two-photon decay channel $h \to \gamma\gamma$ have been addressed in

Ref. [9]. In this channel the branching fraction, measured by the ATLAS collaboration, is larger than the value predicted in the SM by a factor of 1.60 ± 0.30 for $m_h = 125.2 \pm 0.26(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV [10], while the CMS collaboration obtained for this factor 0.77 ± 0.27 for $m_h = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})$ GeV [11]. The author of [9], in framework of a model with vectorlike fermions, showed that the CP violation in the $h \to \gamma\gamma$ decay results in the dependence of the differential decay rate on the angle between linear polarization vectors of the photons. Experimentally, this angular distribution can be measured after both photons are converted into the e^+, e^- pairs via the azimuthal angle distribution between the planes spanned by the two e^+, e^- pairs. In Ref. [12] 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.

In the present paper we would like to address the decay of the Higgs boson to the photon and Z boson, $h \to \gamma Z$, pointing out to a possibility of studying in this decay not only the CP properties of the newly discovered boson, but also the validity of the CPT symmetry. In this connection one can recall Ref. [13] in which the author showed that an observation of the circular polarization of the photon in the neutral pion decay $\pi^0 \to \gamma\gamma$ (or $\eta \to \gamma\gamma$) would signal violation of the CPT symmetry. Indeed, the product $\vec{s}\,\vec{k}$ (where $\vec{s}$ is the photon spin and $\vec{k}$ is its momentum) is P odd and T even. Such a correlation in the π^0 decay arises due to interference of the two terms in the interaction Lagrangian: a scalar $\tilde{c}\pi^0\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$ and a pseudoscalar $c\pi^0 F_{\mu\nu}F^{\mu\nu}$, with $\tilde{c}$ and c being couplings constants and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

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The analysis of [13] demonstrated that a nonzero value of $\vec{s}\,\vec{k}$ correlation may appear due to a non-Hermiticity of the tree-level amplitude, i.e., $\mathrm{Im}\tilde{c} \neq 0$ or/and $\mathrm{Im}c \neq 0$, and/or higher-order loop corrections to the amplitude inducing imaginary part of $\tilde{c}$.

Note that such a correlation in the Higgs boson decay to two transversally polarized Z bosons in connection with possible violation of CPT symmetry has been discussed in [12].

Generally, similar arguments can be applied to the two-photon decay of the Higgs boson with an analogous conclusion. However measurement of the photon circular polarization in the $h \to \gamma\gamma$ decay is a rather difficult task. In the present paper 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. Namely, a nonzero photon circular polarization induces a term $\sim \cos\theta$ in this distribution which can be measured through the forward-backward asymmetry A_{FB}.

In the SM the $h \to \gamma Z$ decay amplitude in the lowest order is determined by the loop contributions [14,15] 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 $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$, 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 CP violating term in $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$. Note that in the SM and theories beyond the SM which are CPT symmetric, there are no sources of non-Hermiticity of $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$ apart from rescattering effects.

The CPT theorem is one of the most profound results of quantum field theory [16]. 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 CPT violation appears due to nonlocality in the string theory, or violation of Lorentz symmetry in the extra dimensional models (see, for example, [17]). 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 [18]. The CPT violating effects in some of these underlying theories, in principle, can be additional sources of non-Hermiticity of effective Lagrangian $\mathcal{L}_{\mathrm{eff}}^{h\gamma Z}$ and hence contribute to 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 [19,20]. 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.

The paper is organized as follows. In Sec. II the effective Lagrangian for $h\gamma\gamma$ and $h\gamma Z$ interactions and coupling constants in the SM and some its extensions are considered. In Sec. III amplitudes and polarization parameters for the decays $h \to \gamma\gamma$ and $h \to \gamma Z$ are specified. Distribution of the $h \to \gamma Z \to \gamma f\bar{f}$ decay in the polar angle, and distribution of the $h \to \gamma^* Z \to \ell^+\ell^- Z$ decay (with $Z \to \bar{f}f$ on mass shell) in the azimuthal angle are obtained. In Sec. IV results of calculation and discussion are presented. In Sec. V we draw conclusions.

II. FORMALISM

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

$$\mathcal{L}_{\mathrm{eff}}^{h\gamma\gamma} = \frac{e^2}{32\pi^2 v}(c_\gamma F_{\mu\nu}F^{\mu\nu}h - \tilde{c}_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}h), \tag{2}$$

$$\begin{aligned}
\mathcal{L}_{\mathrm{eff}}^{h\gamma Z} = \frac{eg}{16\pi^2 v}(&c_{1Z}Z_{\mu\nu}F^{\mu\nu}h - c_{2Z}(\partial_\mu h Z_\nu - \partial_\nu h Z_\mu) \\
&\times F^{\mu\nu} - \tilde{c}_Z Z_{\mu\nu}\tilde{F}^{\mu\nu}h),
\end{aligned} \tag{3}$$

where e is the positron electric charge, g is the $SU(2)_L$ coupling constant and $v = (\sqrt{2}G_{\mathrm{F}})^{-1/2} \approx 246$ 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 $\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}/2$, with convention $\varepsilon_{0123} = +1$. Dimensionless parameters c_γ, c_{1Z}, c_{2Z}, $\tilde{c}_\gamma$, and $\tilde{c}_Z$ are effective coupling constants [21]. As these coupling constants are, in general, complex-valued, the operators (2) and (3) are non-Hermitian, while being local and Lorentz invariant.

It is convenient to write the couplings c_γ and c_{1Z} as the sums of terms in the SM and new physics (NP) beyond the SM: $c_\gamma = c_\gamma^{\mathrm{SM}} + c_\gamma^{\mathrm{NP}}$, $c_{1Z} = c_Z^{\mathrm{SM}} + c_{1Z}^{\mathrm{NP}}$. In the SM, $\tilde{c}_\gamma = c_{2Z} = \tilde{c}_Z = 0$ and their nonzero values come from effects of the NP. The couplings c_γ^{SM} and c_Z^{SM} have small imaginary parts which arise 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)]. In the one-loop order c_γ^{SM} and c_Z^{SM} are given by [15,23,24]

$$c_\gamma^{\mathrm{SM}} = A_1^\gamma(\tau_W) + \sum_f N_f Q_f^2 A_{1/2}^\gamma(\tau_f) \approx -6.60 + 0.08i, \tag{4}$$

$$\begin{aligned}
c_Z^{\mathrm{SM}} &= -A_1^Z(\tau_W, \lambda_W) - \sum_f N_f Q_f g_f A_{1/2}^Z(\tau_f, \lambda_f) \\
&\approx -5.540 + 0.005i,
\end{aligned} \tag{5}$$

where $f = (\ell, q, t)$, $N_f = 1(3)$ for leptons (quarks), Q_f is the charge of the fermion f in units of the electric charge of the positron. Here also $g_f = (2t_{3L,f} - 4Q_f \sin^2\theta_W)/\cos\theta_W$, where $t_{3L,f}$ is the projection of the weak isospin of the f fermion, and θ_W is the weak angle. The one-loop functions A_1^γ, $A_{1/2}^\gamma$, A_1^Z, $A_{1/2}^Z$ are defined in the Appendix. These functions depend on arguments $\tau_W = 4m_W^2/m_h^2$, $\lambda_W = 4m_W^2/m_Z^2$, $\tau_f = 4m_f^2/m_h^2$, $\lambda_f = 4m_f^2/m_Z^2$, with m_h being the mass of the Higgs boson, m_W (m_Z) being the mass of the W (Z) boson, and m_f being the mass of the f-th fermion. Numerical values in (4) and (5) are obtained for $m_h = 126$ GeV using the SM parameters from [25], and the quark masses are chosen according to [26].

The terms c_γ, c_{1Z}, and c_{2Z} above correspond to a CP-even scalar h, while the terms $\tilde{c}_\gamma$ and $\tilde{c}_Z$ indicate a CP-odd pseudoscalar h. The presence of both sets of terms means that h is not a CP eigenstate. Interference of these terms lead to CP violating effects which reveal in polarization states of the photon. Generally, the couplings c_γ^{NP}, c_{1Z}^{NP}, $\tilde{c}_\gamma$, c_{2Z}, $\tilde{c}_Z$ may be complex.

The SM can be considered as effective low-energy theory of an underlying unknown theory at a scale Λ (characteristic scale of the NP) which is much higher than the electroweak scale v. In effective field-theory language [24,27–31], the couplings c_γ^{NP}, c_{1Z}^{NP}, $\tilde{c}_\gamma$, c_{2Z}, $\tilde{c}_Z$ can be obtained from gauge invariant dimension-6 operators such as

$$\mathcal{O}_B = i\frac{g'}{\Lambda^2}(D_\mu H)^\dagger (D_\nu H)B^{\mu\nu},$$

$$\mathcal{O}_W = i\frac{g}{\Lambda^2}(D_\mu H)^\dagger \tau_k (D_\nu H)W_k^{\mu\nu},$$

$$\mathcal{O}_{BB} = \frac{g'^2}{2\Lambda^2}H^\dagger H B_{\mu\nu}B^{\mu\nu},$$

$$\tilde{\mathcal{O}}_{BB} = \frac{g'^2}{2\Lambda^2}H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu},$$

$$\mathcal{O}_{WW} = \frac{g^2}{2\Lambda^2}H^\dagger H W_{k\mu\nu}W_k^{\mu\nu}, \quad (6)$$

$$\tilde{\mathcal{O}}_{WW} = \frac{g^2}{2\Lambda^2}H^\dagger H W_{k\mu\nu}\tilde{W}_k^{\mu\nu},$$

$$\mathcal{O}_{WB} = \frac{g'g}{2\Lambda^2}H^\dagger \tau_k H W_k^{\mu\nu}B_{\mu\nu},$$

$$\tilde{\mathcal{O}}_{WB} = \frac{g'g}{2\Lambda^2}H^\dagger \tau_k H W_k^{\mu\nu}\tilde{B}_{\mu\nu}.$$

Here, g' is the weak hypercharge gauge coupling, $B_{\mu\nu}$ is the field strength tensor for the hypercharge gauge group, $W_k^{\mu\nu}$ is the field strength tensor for the weak $SU(2)$ gauge group ($k = 1, 2, 3$), H represents the Higgs doublet, and τ_k are the Pauli matrices for weak isospin. The operators $\mathcal{O}_i$ are CP even, and $\tilde{\mathcal{O}}_j$ are CP odd. The dual field-strength tensors are defined by $\tilde{X}_{\mu\nu} = (1/2)\varepsilon_{\mu\nu\alpha\beta}X^{\alpha\beta}$, for $X = B$, W_k. The corresponding effective Hamiltonian is

$$\mathcal{H}_{eff}^{(6)} = -\mathcal{L}_{eff}^{(6)} = \sum_i c_i \mathcal{O}_i + \sum_j \tilde{c}_j \tilde{\mathcal{O}}_j, \quad (7)$$

where $i = (B, W, BB, WW, WB)$ and $j = (BB, WW, WB)$. The $h\gamma\gamma$ and $h\gamma Z$ couplings follow from the effective Lagrangian (7) by making the replacement $H \rightarrow (0, (v + h)/\sqrt{2})^T$ in the unitary gauge,

$$c_\gamma^{NP} = \left(\frac{4\pi v}{\Lambda}\right)^2 (c_{WB} - c_{BB} - c_{WW}), \quad (8)$$

$$\tilde{c}_\gamma = \left(\frac{4\pi v}{\Lambda}\right)^2 (\tilde{c}_{BB} + \tilde{c}_{WW} - \tilde{c}_{WB}), \quad (9)$$

$$c_{1Z}^{NP} = \left(\frac{4\pi v}{\Lambda}\right)^2 \sin\theta_W (c_{BB}\tan\theta_W - c_{WW}\cot\theta_W + c_{WB}\cot 2\theta_W), \quad (10)$$

$$c_{2Z} = \left(\frac{2\pi v}{\Lambda}\right)^2 \frac{c_B - c_W}{\cos\theta_W}, \quad (11)$$

$$\tilde{c}_Z = \left(\frac{4\pi v}{\Lambda}\right)^2 \sin\theta_W (\tilde{c}_{WW}\cot\theta_W - \tilde{c}_{BB}\tan\theta_W - \tilde{c}_{WB}\cot 2\theta_W). \quad (12)$$

The effective dimensionless couplings c_B, c_W, c_{BB}, c_{WW}, c_{WB}, $\tilde{c}_{BB}$, $\tilde{c}_{WW}$, and $\tilde{c}_{WB}$ could be of order unity based on naive dimensional analysis [32,33]. If the theory is valid up to a scale $\Lambda \sim 4\pi v$ then it follows from Eqs. (8)–(12) that c_γ^{NP}, c_{1Z}^{NP}, $\tilde{c}_\gamma$, c_{2Z}, $\tilde{c}_Z$ can be of the order unity.

On the other hand, values of coupling constants c_γ^{NP}, c_{1Z}^{NP}, $\tilde{c}_\gamma$, c_{2Z}, $\tilde{c}_Z$ can be calculated in various models. In particular, there are models with more than one Higgs doublet which induce CP violation due to the specific coupling of neutral Higgs bosons to fermions. We calculate c_γ^{NP}, c_{1Z}^{NP}, $\tilde{c}_\gamma$, 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

$$\mathcal{L}^{hff} = -\sum_f \frac{m_f}{v}h\bar{\psi}_f(1 + s_f + ip_f\gamma_5)\psi_f, \quad (13)$$

where 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 $h \rightarrow \gamma\gamma$ and $h \rightarrow \gamma Z$ amplitudes we obtain

$$c_\gamma^{NP} = \sum_f N_f s_f Q_f^2 A_{1/2}^\gamma(\tau_f)$$

$$\approx 1.84 s_t - (3s_b + 2s_c + 2s_\tau) \times 10^{-2}$$

$$+ i2(2s_b + s_c + s_\tau) \times 10^{-2}, \quad (14)$$

$$\tilde{c}_\gamma = -2\sum_f N_f p_f Q_f^2 \tau_f f(\tau_f)$$
$$\approx 2.79 p_t + (3p_b + 2p_c + 2p_\tau) \times 10^{-2}$$
$$- i2(2p_b + p_c + p_\tau) \times 10^{-2}, \qquad (15)$$

$$c_{1Z}^{NP} = -\sum_f N_f s_f Q_f g_f A_{1/2}^Z(\tau_f, \lambda_f)$$
$$\approx 0.3253 s_t - (8.2s_b + 1.2s_c + 0.2s_\tau) \times 10^{-3}$$
$$+ i(4.8s_b + 0.5s_c + 0.1s_\tau) \times 10^{-3}, \qquad (16)$$

$$\tilde{c}_Z = -\sum_f N_f p_f Q_f g_f I_2(\tau_f, \lambda_f)$$
$$\approx -0.4939 p_t + (9.6p_b + 1.3p_c + 0.3p_\tau) \times 10^{-3}$$
$$- i(4.9p_b + 0.5p_c + 0.1p_\tau) \times 10^{-3}, \qquad (17)$$

where one-loop functions $f(\tau_f)$, $I_2(\tau_f, \lambda_f)$ are specified in the Appendix, and their arguments τ_f, λ_f are defined after Eq. (5).

In obtaining the numerical values in (14)–(17) we have taken into account dominant contributions from the charm, bottom, top quarks and τ lepton, in particularly, the charm, bottom quarks and τ lepton give rise to the imaginary parts of the couplings in (14)–(17).

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

$$\Gamma(h \rightarrow f\bar{f}) = \frac{N_f G_F}{4\sqrt{2}\pi} m_f^2 m_h \beta_f ((1 + s_f)^2 \beta_f^2 + p_f^2), \qquad (18)$$

where $\beta_f = \sqrt{1 - 4m_f^2/m_h^2}$ is velocity of fermion $f = (\ell, q)$ in the rest frame of h. 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. (18) coincides with the decay width of the SM Higgs boson.

III. AMPLITUDES AND ANGULAR DISTRIBUTIONS

Let us consider the decay of the zero-spin Higgs h boson into a pair of photons

$$h(p) \rightarrow \gamma(k_1, \epsilon_1)\gamma(k_2, \epsilon_2), \qquad (19)$$

where p is the four-momentum of h boson, k_1, k_2 are the four-momenta of photons and ϵ_1, ϵ_2 are the corresponding polarization four-vectors. In the rest frame of h, the amplitude of this decay can be written in the form

$$\mathcal{A}(h \rightarrow 2\gamma) = \frac{e^2 m_h^2}{16\pi^2 v}(c_\gamma(\vec{e}_1^* \vec{e}_2^*) + \tilde{c}_\gamma(\hat{\vec{k}}[\vec{e}_1^* \times \vec{e}_2^*])), \quad (20)$$

where m_h is the mass of h boson. The polarization vectors are chosen in the form $\epsilon_1 = (0, \vec{e}_1)$, $\epsilon_2 = (0, \vec{e}_2)$, where

$\vec{e}_1\vec{k} = \vec{e}_2\vec{k} = 0$, $\vec{k}$ is the three-momentum of one of the photons and $\hat{\vec{k}} \equiv \vec{k}/|\vec{k}|$.

The helicity amplitudes for decay (19) are equal to

$$H_\pm = -\frac{e^2 m_h^2}{16\pi^2 v}(c_\gamma \pm i\tilde{c}_\gamma). \qquad (21)$$

The decay width of $h \rightarrow 2\gamma$ is

$$\Gamma(h \rightarrow 2\gamma) = \frac{1}{32\pi m_h}(|H_+|^2 + |H_-|^2). \qquad (22)$$

The polarization states of a single photon are usually described through the density matrix $\rho^{(\gamma)}$. For the process (19), one can write the two-photon density matrix following Ref. [34] as follows:

$$\rho^{(\gamma\gamma)} = \frac{1}{4}(1 \otimes 1 - \sigma_3 \otimes \sigma_3 + \xi_1(\sigma_1 \otimes \sigma_2 - \sigma_2 \otimes \sigma_1)$$
$$+ \xi_2(\sigma_3 \otimes 1 - 1 \otimes \sigma_3) - \xi_3(\sigma_1 \otimes \sigma_1 + \sigma_2 \otimes \sigma_2)), \qquad (23)$$

where $\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$ are the Pauli matrices, 1 is 2×2 unit matrix, and $\otimes$ means the direct product of two matrices. The reference frame is chosen with the OZ axis along $\hat{\vec{k}}$, and matrices on the left (right) from symbol $\otimes$ refer to the photon with momentum $\vec{k}$ ($-\vec{k}$).

In (23) the following parameters are introduced:

$$\xi_1 = \frac{2\,\text{Im}(H_+ H_-^*)}{|H_+|^2 + |H_-|^2} = \frac{2\,\text{Re}(c_\gamma \tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2},$$

$$\xi_2 = \frac{|H_+|^2 - |H_-|^2}{|H_+|^2 + |H_-|^2} = \frac{2\,\text{Im}(c_\gamma \tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2}, \qquad (24)$$

$$\xi_3 = -\frac{2\,\text{Re}(H_+ H_-^*)}{|H_+|^2 + |H_-|^2} = \frac{|\tilde{c}_\gamma|^2 - |c_\gamma|^2}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2}.$$

The Stokes parameter ξ_2 defines degree of the circular polarization of the photon with momentum $\vec{k}$, it has the meaning of average photon helicity. Parameters ξ_1, ξ_3 define correlation of linear polarizations of two photons (in particular, for $\xi_1 = 0$, $\xi_3 = -1$ the linear polarizations are parallel, while for $\xi_1 = 0$, $\xi_3 = 1$ they are orthogonal).

Next we come to the decay of h to γ and Z boson

$$h(p) \rightarrow \gamma(k_1, \epsilon_1)Z(k_2, \epsilon_2), \qquad (25)$$

where k_1, (k_2) is the four-momentum of photon (Z boson), ϵ_1, (ϵ_2) is polarization vector of the photon (Z boson).

The helicity amplitudes for the decay (25) are

$$H_\pm = -\frac{egm_h^2}{16\pi^2 v}\left(1 - \frac{m_Z^2}{m_h^2}\right)(c_{1Z} + c_{2Z} \pm i\tilde{c}_Z), \quad (26)$$

with the decay width

$$\Gamma(h \to \gamma Z) = \frac{1}{16\pi m_h}\left(1 - \frac{m_Z^2}{m_h^2}\right)(|H_+|^2 + |H_-|^2), \quad (27)$$

where m_Z is the Z boson mass.

From definitions (24) we find the polarization parameters

$$\xi_1 = -\frac{2\,\text{Im}(A_\parallel A_\perp^*)}{|A_\parallel|^2 + |A_\perp|^2},$$

$$\xi_2 = \frac{2\,\text{Re}(A_\parallel A_\perp^*)}{|A_\parallel|^2 + |A_\perp|^2}, \quad (28)$$

$$\xi_3 = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\parallel|^2 + |A_\perp|^2},$$

where $H_\pm$ from Eq. (26) for further convenience are replaced by the amplitudes $A_\parallel = (H_+ + H_-)/\sqrt{2}$ and $A_\perp = (H_+ - H_-)/\sqrt{2}$ corresponding to linearly polarized final states.

Numerical values of parameters ξ_1, ξ_2, ξ_3 will be discussed in Sec. IV.

In the decay (25), due to the zero-spin nature of the Higgs boson, the photon and Z boson have equal helicities. This allows for measurement of the photon circular polarization through the decay $h \to \gamma Z \to \gamma f\bar{f}$ [35]. Indeed, we derive the following angular distribution of the process 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,

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

$$(29)$$

where

$$A^{(f)} \equiv \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}. \quad (30)$$

The vector g_V^f and axial-vector g_A^f constants are

$$g_V^f \equiv t_{3L,f} - 2Q_f\sin^2\theta_W, \qquad g_A^f \equiv t_{3L,f}. \quad (31)$$

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),

$$A_{\text{FB}} \equiv \frac{F - B}{F + B}, \quad (32)$$

where

$$F \equiv \int_0^1 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}d\cos\theta, \qquad B \equiv \int_{-1}^0 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}d\cos\theta,$$

which is

$$A_{\text{FB}} = -\frac{3}{4}A^{(f)}\xi_2, \quad (33)$$

allows one to find ξ_2.

Note that $A^{(\mu)}$ for the decay

$$h \to \gamma Z \to \gamma\mu^-\mu^+ \quad (34)$$

is 0.142 ± 0.015 [25], therefore in view of the condition $|\xi_2| \le 1$, the absolute value of the asymmetry for this decay is not larger than 0.11. At the same time for the decay channel

$$h \to \gamma Z \to \gamma b\bar{b} \quad (35)$$

($A^{(b)} = 0.923 \pm 0.020$ [25]), the absolute value of A_{FB} can be much larger, namely, as large as 0.69.

Consider now feasibility to measure the distribution (29) at the LHC after its upgrade to higher luminosity and energy $\sqrt{s} = 14$ TeV. Taking into account various mechanisms of Higgs boson production in pp collisions, the inclusive cross section is $\sigma = 57.0163$ pb [26]. Then the cross section for the process $pp \to hX \to \gamma ZX \to \gamma\ell^+\ell^- X$ in the SM is

$$\sigma \times \text{BR}(h \to \gamma Z)\text{BR}(Z \to \ell^+\ell^-) = 6.24 \text{ fb}, \quad (36)$$

where $\ell = e, \mu$ and the branching fractions are taken from Refs. [25,36]. In order to observe the forward-backward asymmetry A_{FB} for maximal value $|\xi_2| = 1$ at a 3σ 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}.

Let us discuss a possibility to determine the polarization parameters ξ_1 and ξ_3. For this one can study the process

$$h \to \gamma^* Z \to \ell^+\ell^- Z \quad (37)$$

with the decay $Z \to \bar{f}f$ on mass shell. For the process (37) we obtain the distribution over the dilepton invariant mass squared q^2 and azimuthal angle ϕ between the decay planes of $\gamma^* \to \ell^+\ell^-$ and $Z \to \bar{f}f$ in the h rest frame,

$$\frac{d\Gamma(h \to \ell^+\ell^- Z)}{dq^2 d\phi}\bigg/\frac{d\Gamma}{dq^2}$$

$$= \frac{1}{2\pi}\left(1 - \frac{1}{4}(1 - F_L(q^2))(\xi_3(q^2)\cos 2\phi + \xi_1(q^2)\sin 2\phi)\right).$$

$$(38)$$

Here

$$F_L(q^2) \equiv \frac{|A_0(q^2)|^2}{|A_0(q^2)|^2 + |A_\parallel(q^2)|^2 + |A_\perp(q^2)|^2} \quad (39)$$

is the fraction of longitudinal polarization of virtual photon, and the amplitudes are defined as

$$A_0(q^2) = \frac{eg}{16\pi^2 v}\sqrt{\frac{q^2}{m_Z^2}}(2c_{1Z}m_Z^2 + c_{2Z}(m_h^2 - q^2 + m_Z^2)),$$

$$(40)$$

$$A_\parallel(q^2) = -\frac{eg}{8\sqrt{2}\pi^2 v}(c_{1Z}(m_h^2 - q^2 - m_Z^2)$$
$$+ c_{2Z}(m_h^2 + q^2 - m_Z^2)), \qquad (41)$$

$$A_\perp(q^2) = -i\frac{eg}{8\sqrt{2}\pi^2 v}\tilde{c}_Z\sqrt{\lambda(m_h^2, q^2, m_Z^2)}, \qquad (42)$$

with $\lambda(a, b, c) \equiv a^2 + b^2 + c^2 - 2(ab + ac + bc)$ and the distribution over the invariant mass squared reads

$$\frac{d\Gamma}{dq^2} = \frac{\alpha_{\mathrm{em}}\sqrt{\lambda(m_h^2, q^2, m_Z^2)}}{48\pi^2 m_h^3 q^2}(|A_0(q^2)|^2 + |A_\parallel(q^2)|^2$$
$$+ |A_\perp(q^2)|^2), \qquad (43)$$

where $\alpha_{\mathrm{em}} = e^2/(4\pi)$ is the electromagnetic fine-structure constant. The q^2-dependent quantities $\xi_1(q^2)$ and $\xi_3(q^2)$ can be obtained from Eqs. (28) in which the amplitudes $A_\parallel(A_\perp)$ are substituted by the q^2-dependent amplitudes $A_\parallel(q^2)(A_\perp(q^2))$. In derivation of (38) we assumed that leptons are massless.

In expressions (40)–(42) we did not take into account additional two-fermion current operators of dimension 6 [27,30] in the effective Hamiltonian (7) and the process $h \to Z^*Z \to \ell^+\ell^- Z$. Both these mechanisms contribute at tree level to the decay $h \to \ell^+\ell^- Z$.

From (38) one can approximately find ξ_1 and ξ_3 in the decay $h \to \gamma Z$. Neglecting the amplitude (40) for longitudinally polarized photon $|A_0(q^2)|^2 \sim q^2$, and q^2-dependence of the transverse amplitudes, i.e., substituting $A_\parallel(q^2) \approx A_\parallel(0)$ and $A_\perp(q^2) \approx A_\perp(0)$, we obtain the distribution over the azimuthal angle

$$\frac{d\Gamma(h \to \ell^+\ell^- Z)}{d\phi} \approx \left(\frac{\alpha_{\mathrm{em}}}{3\pi}\log\frac{q_{\max}^2}{q_{\min}^2}\right)\Gamma(h \to \gamma Z)\frac{1}{2\pi}$$
$$\times \left(1 - \frac{1}{4}(\xi_3\cos 2\phi + \xi_1\sin 2\phi)\right). \qquad (44)$$

The lower integration limit $q_{\min}^2$ is determined by possibilities of detectors, in particular, to provide sufficient ϕ resolution to separate $\sin 2\phi$ and $\cos 2\phi$ terms in the distribution (44). In this connection we should mention recent measurements of the $B^0 \to K^{*0}e^+e^-$ branching fraction [37], in which the LHCb detector allowed selection of the lower value of dilepton invariant mass equal to 30 MeV.

Theoretical accuracy of Eq. (44) improves with the decreasing value of $q_{\max}^2$, since contribution of the competing mechanism $h \to Z^*Z \to \ell^+\ell^- Z$ diminishes for $q_{\max}^2 \ll m_Z^2$. Consider for example production of the e^+e^- pair in the process $h \to e^+e^- Z$ with dilepton invariant mass from 30 MeV to 1000 MeV. Our calculation including both $h \to \gamma^*Z \to e^+e^- Z$ and $h \to Z^*Z \to e^+e^- Z$ amplitudes shows that theoretical error in ξ_1, ξ_3, which arises when neglecting the $h \to Z^*Z \to e^+e^- Z$ mechanism, amounts to

20% in the SM (in which $\xi_1^{\mathrm{SM}} = 0$, $\xi_3^{\mathrm{SM}} = -1$), and 10% in the effective Hamiltonian approach (7) [the choice of coefficients (8)–(12) is discussed in Sec. IV].

Of course, the process $h \to \gamma^*Z \to e^+e^- Z$ is rare. Let us make an estimate of its observability at the LHC energy $\sqrt{s} = 14$ TeV. Using (44) and choosing the Higgs production inclusive cross section $\sigma = 57.0163$ pb [26] we calculate the SM cross section for the $pp \to hX \to \gamma^*ZX \to e^+e^- ZX$ in the interval of dilepton invariant mass from 30 MeV to 1000 MeV,

$$\sigma \times \frac{\Gamma(h \to e^+e^- Z)|_{30<m_{ee}<1000\ \mathrm{MeV}}}{\Gamma(h \to \mathrm{all})} = 0.5\ \mathrm{fb}. \qquad (45)$$

When detecting Z boson via $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ channels the cross section (45) is reduced by factor 0.067, and for the integrated luminosity of 100 fb^{-1} we can expect about 3 events. This number is too small and a higher integrated luminosity will be needed to observe the decay $h \to \gamma^*Z \to \ell^+\ell^- Z$ and analyze its angular distribution.

IV. 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 (i) the approach in which NP is expressed through dimension-6 operators described by effective Hamiltonian (7), and (ii) the model (13) with the scalar and pseudoscalar couplings of fermions to the Higgs boson.

In the approach (7) we take for definiteness $c_B = c_W = 1$, $c_{WB} = c_{BB} = c_{WW} = 1$, $\tilde{c}_{WB} = \tilde{c}_{BB} = \tilde{c}_{WW} = 1$. Choosing the scale $\Lambda = 4\pi v \approx 3.1$ TeV we obtain for the $h \to \gamma\gamma$ decay

$$\xi_1 = -0.259, \qquad \xi_2 = 0.003, \qquad \xi_3 = -0.966,$$
$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(h \to \gamma\gamma)}{\Gamma^{\mathrm{SM}}(h \to \gamma\gamma)} = 1.35, \qquad (46)$$

and for $h \to \gamma Z$ decay

$$\xi_1 = -0.107, \qquad \xi_2 = 0.0001, \qquad \xi_3 = -0.994,$$
$$\mu_{\gamma Z} \equiv \frac{\Gamma(h \to \gamma Z)}{\Gamma^{\mathrm{SM}}(h \to \gamma Z)} = 1.12. \qquad (47)$$

For another scale $\Lambda = 2$ TeV, for the $h \to \gamma\gamma$ decay, we obtain

$$\xi_1 = -0.497, \qquad \xi_2 = 0.004,$$
$$\xi_3 = -0.868, \qquad \mu_{\gamma\gamma} = 1.99, \qquad (48)$$

and for $h \to \gamma Z$ decay,

$$\xi_1 = -0.236, \qquad \xi_2 = 0.0002,$$
$$\xi_3 = -0.972, \qquad \mu_{\gamma Z} = 1.31. \tag{49}$$

For the ratio $\mu_{\gamma\gamma}$ our calculation with the scale $\Lambda = 4\pi v$ better agrees with the ATLAS data [10] for $h \to \gamma\gamma$ than calculation with $\Lambda = 2$ TeV.

In the model with scalar and pseudoscalar couplings of fermions to the Higgs boson (13) we choose the parameters

$$p_t = p_b = p_c = p_\tau = \pm 1/\sqrt{2},$$
$$s_t = s_b = s_c = s_\tau = 1/\sqrt{2} - 1, \tag{50}$$

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

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

$$\xi_1 = \mp 0.528, \qquad \xi_2 = \mp 0.010,$$
$$\xi_3 = -0.849, \qquad \mu_{\gamma\gamma} = 1.26, \tag{51}$$

and for decay $h \to \gamma Z$,

$$\xi_1 = \pm 0.121, \qquad \xi_2 = \mp 0.001,$$
$$\xi_3 = -0.993, \qquad \mu_{\gamma Z} = 1.04. \tag{52}$$

In addition, the $h \to f\bar{f}$ decay width calculated with s_f, p_f in (50) coincides with the SM decay width and agrees with the CMS data [11] for $h \to \tau^+ \tau^-$ and $h \to b\bar{b}$ decays,

$$\mu_{\tau\tau} \equiv \frac{\Gamma(h \to \tau^+ \tau^-)}{\Gamma^{\mathrm{SM}}(h \to \tau^+ \tau^-)} = 1.10 \pm 0.41,$$
$$\mu_{bb} \equiv \frac{\Gamma(h \to b\bar{b})}{\Gamma^{\mathrm{SM}}(h \to b\bar{b})} = 1.15 \pm 0.62. \tag{53}$$

At the same time the channel $h \to c\bar{c}$ is not measured yet. Thus the $h \to c\bar{c}$ width, in general, may differ from the SM prediction, and consequently the constraint $(1 + s_c)^2 + p_c^2 = 1$ for the charm quark may not hold. We can make an assumption that $\Gamma(h \to c\bar{c}) \le \Gamma(h \to b\bar{b})$. Combining this inequality with Eqs. (18) and (53) we find

$$(1 + s_c)^2 + p_c^2 \le \mu_{bb} \times \frac{\Gamma^{\mathrm{SM}}(h \to b\bar{b})}{\Gamma^{\mathrm{SM}}(h \to c\bar{c})}. \tag{54}$$

Taking the central values of μ_{bb} and the widths from [36] (Table 1 therein) we obtain the following constraint for the $hc\bar{c}$ couplings: $(1 + s_c)^2 + p_c^2 \le 22.8$.

To estimate maximal values of polarization parameter ξ_2 in the channel $h \to \gamma Z$ let us take s_c, p_c satisfying $(1 + s_c)^2 + p_c^2 = 22.8$, although the latter equality does not fix s_c, p_c uniquely. In addition, put $s_f = p_f = 0$ for $f \ne c$. Then calculation using (16) and (17) gives values of ξ_2 which do not exceed 8.6×10^{-4}. It is seen that even for such a radical modification of the Higgs couplings to the charm quarks, the parameter ξ_2 remains very small.

Thus the existing data on the Higgs boson decay to the $\tau^+ \tau^-$ and $b\bar{b}$ pairs and a reasonable assumption on the

upper bound of the decay width to the charm quarks lead to conclusion that the rescattering effects on the one-loop level result in values of ξ_2 in the $h \to \gamma Z$ decay about 10^{-3} or smaller.

It would be of interest to check in the experimental analysis of the distribution (29) 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 effective Lagrangian. The latter may arise, for example, due to the breaking of Hermiticity in an underlying (fundamental) theory at very small distances. Note that similar aspects have been discussed in [38] for the process $\gamma\gamma \to h$, where the authors calculated various asymmetries as functions of complex coefficients c_γ, $\tilde{c}_\gamma$ in Eq. (2). Since the requirement of Hermiticity is one of the conditions in the proof of the CPT theorem [16], 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 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.

V. CONCLUSIONS

In this paper polarization properties of the $\gamma\gamma$ and γZ states in the decays $h \to \gamma\gamma$ and $h \to \gamma Z$ of recently discovered scalar boson have been considered. We have chosen effective Lagrangian, describing $h\gamma\gamma$ and $h\gamma Z$ interactions 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 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.

In numerical estimates of these parameters we included the one-loop contribution from the SM, and models beyond the SM. Namely, we applied the approach [24,27–31] in which NP is described by dimension-6 operators in the fields of the SM, and model with scalar and pseudoscalar couplings of fermions to the Higgs boson on the one-loop level.

The value of photon circular polarization turns out to be very small, of the order 10^{-3}. In general, a nonzero value of ξ_2 arises due to presence of the CP-even and CP-odd parts in 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 recent CMS data on the $h \to \tau^+\tau^-$ and $h \to b\bar{b}$ decays, and couplings to the charm quark are constrained from an assumption on the upper bound of the $h \to c\bar{c}$ decay width.

Apart from rescattering effects, in framework of *CPT* symmetric models, there are no sources of non-Hermiticity of $\mathcal{L}_{\rm eff}^{h\gamma Z}$ which could contribute to parameter ξ_2. If there is a violation of *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 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 *CPT* violation in an underlying theory.

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

We also estimated in the SM a feasibility of measurement of the discussed processes in the pp collisions at the LHC, after its upgrade to energy $\sqrt{s} = 14$ TeV and higher luminosity. The cross section for the process $pp \to hX \to \gamma ZX \to \gamma \ell^+\ell^- X$ ($\ell = e, \mu$) turns out to be 6.24 fb. With integrated luminosity about 120 fb^{-1} and ideal detector it may be possible to observe the forward-backward asymmetry $A_{\rm FB}$ for $|\xi_2| = 1$ at a 3σ level.

Here we should mention papers [39,40], where possibilities of studying at the LHC the $h \to \gamma\ell^+\ell^-$ decay via γZ channel are considered. Although observation of the Higgs is difficult in view of the background which is a few orders of magnitude larger than the signal and unfavorable kinematics of this decay [40], in these papers optimistic conclusions are made as for measurement of the branching ratio of the SM Higgs decay to γZ at the 14 TeV LHC with integrated luminosity of 100 fb^{-1} [39].

The reaction $pp \to hX \to \gamma^* ZX \to e^+e^- ZX$ is a more rare process, and our estimate of its observability is less optimistic. One can expect about 3 events in the interval of e^+e^- invariant mass from 30 MeV to 1000 MeV if Z boson

is detected through the $Z \to e^+e^-$, $\mu^+\mu^-$ channels. Clearly an integrated luminosity higher than 100 fb^{-1} will be needed to study the $h \to \gamma^* Z \to e^+e^- Z$ process.

In conclusion, we hope that with increasing the integrated luminosity at the LHC investigation of angular distributions discussed in the present paper will become possible.

APPENDIX: DEFINITION OF LOOP FUNCTIONS

The loop functions for the $W^{\pm}$ boson ($A_1^{\gamma(Z)}$) as well as the fermion f ($A_{1/2}^{\gamma(Z)}$) are defined in Ref. [23],

$$A_1^{\gamma}(\tau) = -(2 + 3\tau + 3\tau(2 - \tau)f(\tau)), \qquad (A1)$$

$$A_{1/2}^{\gamma}(\tau) = 2\tau(1 + (1 - \tau)f(\tau)), \qquad (A2)$$

$$A_1^Z(\tau, \lambda) = \cos\theta_W\Big(4(3 - \tan^2\theta_W)I_2(\tau, \lambda)$$
$$+ \Big(\Big(1 + \frac{2}{\tau}\Big)\tan^2\theta_W - \Big(5 + \frac{2}{\tau}\Big)\Big)I_1(\tau, \lambda)\Big),$$
$$(A3)$$

$$A_{1/2}^Z(\tau, \lambda) = I_1(\tau, \lambda) - I_2(\tau, \lambda). \qquad (A4)$$

The functions I_1, I_2 are given by

$$I_1(\tau, \lambda) = \frac{\tau\lambda}{2(\tau - \lambda)}\Big(1 + \frac{\tau\lambda}{\tau - \lambda}(f(\tau) - f(\lambda))$$
$$+ \frac{2\tau}{\tau - \lambda}(g(\tau) - g(\lambda))\Big), \qquad (A5)$$

$$I_2(\tau, \lambda) = -\frac{\tau\lambda}{2(\tau - \lambda)}(f(\tau) - f(\lambda)), \qquad (A6)$$

where the functions $f(\tau)$ and $g(\tau)$ can be expressed as

$$f(\tau) = \begin{cases} \arcsin^2\frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\Big(\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\Big)^2 & \tau < 1, \end{cases} \qquad (A7)$$

$$g(\tau) = \begin{cases} \sqrt{\tau - 1}\arcsin\frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ \frac{\sqrt{1-\tau}}{2}\Big(\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\Big) & \tau < 1. \end{cases} \qquad (A8)$$

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