Two-photon Higgs width and triple Higgs coupling in 2HDM at SM-like scenario

I. F. Ginzburg
Sobolev Institute of Mathematics,
Novosibirsk State University
Novosibirsk, Russia

Within 2HDM sizable deviations of the two-photon Higgs width and the value of triple Higgs coupling from their values in the SM are connected to each other. If SM-like scenario for the observed Higgs boson is realized, mentioned deviations can be visible either simultaneously (in very exotic cases) or inaccessible for observation at the LHC.

We use relative couplings

$$\chi_a^P = \frac{g_a^P}{g_{SM}^P}, \quad (P = W, Z, t, b, \tau, ...); \quad \chi_a^{H^+W^-} = \frac{g(H^+W^-h_a)}{M_W/v}, \quad \chi_a^{\pm} = \frac{g(H^+H^{\dots}}{2M_{\pm}^2/\dots}$$

(Note: $\chi_1^{\pm} = 1$ for *would be* charged scalar $H^{\pm}$, interacting with Higgs only via $\Delta L = \tilde{\Lambda}(H^+H^-)\phi^2$).

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The neutrals h_a generally have no definite CP parity. Couplings χ_a^V and $\chi_a^{\pm}$ are real, while other couplings are generally complex. The $Re(\chi_a^f)$ and $Im(\chi_a^f)$ are responsible for the interaction of fermion f to CP-even and CP-odd parts of h_a respectively. (In particular, for the CP-conserving case with $h_3 = A$ we have $Im(\chi_{2,1}^f) = 0$, $Re(\chi_3^f) = 0$).

The relative couplings obey the following sum rules:

$$\sum_a (\chi_a^V)^2 = 1 \,, \qquad |\chi_a^V|^2 + |\chi_a^{H^\pm W^\mp}|^2 = 1 \,, \qquad \sum_a (\chi_a^f)^2 = 1 \,.$$

Some of them are known in CP conserving 2HDM with some definite forms of Yukawa interaction.

The minimal complete set of measurable quantities (observables)

determines all parameters of the most general Higgs Lagrangian. This set is subdivided naturally into two subsets (hep-ph:1502.06346).

(a) v.e.v. of Higgs field $v = 246$ GeV, masses of all Higgs bosons $M_{1,2,3}$, $M_\pm$ and two of three couplings χ_a^V.

(b) Three triple couplings $H^+H^-h_a$ (quantities $\chi_a^\pm$) and one quartic coupling $g(H^+H^-H^+H^-)$.

In the most general 2HDM, all these observables are independent of each other. Their possible values are only limited by general conditions, such as positivity and sum rules. In some special variants of 2HDM, additional relations between these parameters may appear (in the CP conserving case we have $\chi_3^V = 0$, $\chi_3^\pm = 0$).

SM-like scenario

Experimental data are in favor that the Nature realizes SM-like scenario:

1) Single observed Higgs boson h_1 has mass $M \approx 125$ GeV.

2) Its couplings to fundamental particles P (gauge bosons V and fermions f) are close to the SM expectations within experimental accuracy:

$$\varepsilon_P = \left|1 - |\chi_1^P|^2\right| \ll 1 \qquad (P = V(W,\, Z), \quad f = (t,\, b,\, \tau, ...))\,.$$

Today this statement remains only a plausible hypothesis until the couplings are measured with sufficient accuracy. The W-fusion experiments are of the greatest interest here.

Some couplings in the SM-like scenario

Sum rules results in

$$(a)|\chi_a^V|^2 < \varepsilon_V \ll 1\,, \quad a=2,3\,; \qquad (b)|\chi_a^{W^\pm H^\mp}|^2 \approx 1\,; \quad (c)\ |\chi_1^{W^\pm H^\mp}|^2 \sim \varepsilon_V \ll$$

Relation (a) means that h_2, h_3 are gaugefobic.

Higgs two-photon width

It is described by well known equations

$$\Gamma_a^{\gamma\gamma} = \frac{\alpha^2 M_a^3}{256\pi^3 v^2}\left(|\Phi_a^{E\gamma}|^2 + |\Phi_a^{O\gamma}|^2\right) . \qquad (1)$$

Quantities $\Phi_a^{E\gamma}$ and $\Phi_a^{O\gamma}$ are the sums of the well known contributions $\Phi_J(r_a^P)$ of different charged particles P with mass M_P and spin J, circulating in loops (superscript E and O mark CP-even and CP-odd quark loop contributions).

$$\begin{gathered}
\Phi_a^{E\gamma} = \chi_a^V \Phi_1(r_a^W) + \sum_f Re(\chi_a^f) N_c Q_f^2\, \Phi_{1/2}^E(r_a^f) + \chi_a^{\pm}\Phi_0(r_a^{\pm}) \,, \\
\Phi_a^{O\gamma} = \sum_f Im(\chi_a^f) N_c Q_f^2 \Phi_{1/2}^O(r_a^f) \,; \qquad r_a^P = \frac{4M_P^2}{M_a^2} \,.
\end{gathered} \qquad (2)$$

The latest data show that $\Gamma(h_1 \to \gamma\gamma)$ is close to its SM value. In assuming h_1 to be CP-even and $|\chi_1^\pm| \lesssim 1$, these observations provide a basis for the claim that $\chi_1^V \approx 1$ and $\chi_1^t \approx 1$ (SM-like scenario). In accordance with our 15 year old papers (IFG, M. Krawczyk, P. Olsen)
(i) Contribution from charged Higgs loop with $\chi_1^\pm \approx 1$ reduces $\Gamma(h_1 \to \gamma\gamma)$ by about 10% (that is within accuracy of modern data).
(ii) At $\chi_1^t \approx -1$ the width $\Gamma(h_1 \to \gamma\gamma)$ increases by factor about 2.5.
The latter fact means that the value of $\Gamma(h_a \to \gamma\gamma)$, close to SM value, can be obtained not only at $\chi_1^t \approx 1$ but also at negative χ_1^t with $|\chi_1^t| < 1$. Similar conclusions were obtained at recent detail analysis of modern data (see e.g. Belanger et al, hep-ph: 1212.5244).
The cases of big $|\chi_1^\pm|$ and big CP-odd admixture in h_1 were not explored in details till now.
Measuring of h_1WW and $h_1t\bar{t}$ couplings together with CP asymmetry in $h_1t\bar{t}$ are very important tasks.

Gluon fusion

The cross section of gluon fusion is given by the t quark loop integrals written for two-photon width. In the one-loop approximation it is expressed via the cross section $\sigma(gg \to h_{SM}^{wb}(M_a))$ for *would be* SM Higgs boson with mass M_a:

$$\sigma(gg \to h_a) = \sigma(gg \to h_{SM}^{wb}(M_a)) \left[(Re\chi_a^t)^2 + (Im\chi_a^t)^2 \Phi^{O/E}(r_a^t) \right],$$

$$where \quad \Phi^{O/E}(r) = \left(\Phi_{1/2}^{O}(r) / \Phi_{1/2}^{E}(r) \right)^2 .$$

For $M_a = 125$ GeV and 300 GeV we have $\Phi^{O/E} \approx 2.25$ and 2.7 respectively.

I don't meet data analysis with taking part C-odd contribution of t.

Triple Higgs coupling

The measuring of $g(h_1 h_1 h_1)$ is scheduled in the LHC and other colliders. The accuracy of these measurements can not be high, since in each case corresponding experiments deal with interference of two channels with identical final state – an independent production of two Higgses and production of Higgses via $h_1 h_1 h_1$ vertex. This interference is mainly destructive (D.A. Dicus et al. hep-ph: arXiv:1504.02334). For example, for 100 TeV hadron collider with total luminosity 3/*abn* one can hope to reach accuracy 40% in the extraction of this vertex (A.Barr et al. hep-ph:1412.7154).

The equation for triple Higgs coupling via observables in the most general 2HDM was found in the IFG+K.Kanishev, hep-ph:1502.06346:

$$g(h_1h_1h_1) = \frac{M_1^2}{v}\chi_{111}; \quad \chi_{111} = \chi_1^V\left\{1+\left(1-(\chi_1^V)^2\right)\left[1+\sum_b 2\frac{M_b^2}{M_1^2}(\chi_b^V)^2\right]+\right.$$
$$\left.+\left(1-(\chi_1^V)^2\right)\frac{2M_\pm^2}{M_1^2}\left[\sum_b \chi_b^V\chi_b^\pm - 1 + Re\left(\sum_b \chi_b^{H^+W^-}\chi_b^\pm\frac{\chi_1^{H^+W^-}}{\chi_1^V}\right)\right]\right\}. \tag{3}$$

Here factor M_1^2/v is the SM result, and $\chi_{111}-1$ represents the New Physics effect.

In the SM-like scenario $(1-(\chi_1^V)^2 \equiv \varepsilon_V \ll 1)$

$$\chi_{111} \approx (1-\varepsilon_V/2)\left\{1+\varepsilon_V\left[3+B\varepsilon_V+2B_\pm\left(\chi_1^\pm - 1+\varepsilon_V K_\pm\right)\right]\right\},$$
$$B \sim \sum_b M_b^2/M_1^2; \quad B_\pm = 2M_\pm^2/M_1^2, \quad K_\pm \sim \chi_b^\pm, (b=2,3). \tag{4}$$

At moderate values of parameters, relative coupling χ_{111} is close to 1, and it is difficult to expect sizable effect for the particular CP conserving case and with moderate values of parameters such conclusion was obtained in A. Efrati, Y.F. Nir, hep-ph:1401.0935; J. Baglio et al. *Phys. Rev.* **D 90**, *015008 (2014), hep-ph:1403.1264*.

Special exotic values of model parameters providing sizable deviations of triple Higgs coupling from its SM value
(for numbers we use $\varepsilon_1^V \approx 0.1$ and require $|\chi(h_1h_1h_1) - 1| \geq 1$).

◊ Large value of $B_\pm\, \chi_1^\pm$ product. Even at moderate value of charged Higgs mass the big value of vertex $H^+H^-h_1$ result in sizable deviation of $g(h_1h_1h_1)$ from its SM value and simultaneously to big effect in $\Gamma(h_1 \to \gamma\gamma\,)$.

◊ One or both of Higgs neutrals $h_{2,3}$ are heavier than a few TeV. Direct discovery of such Higgs seems to be a difficult task. Therefore for a long time detection of this phenomenon may become important source of knowledge about these heavy neutrals.

◊ Large couplings $\chi_a^\pm \gtrsim 10$. In this case the two-photon width $h_a \to \gamma\gamma$ will be strongly different from that for the would-be SM Higgs with the same mass.

• Special case appears in the SM-like scenario at 400 GeV$> M_2 >$ 250 GeV if $|\chi_2^t| > 1$. In this case Higgs boson h_2 is relatively narrow and the cross section of gluon fusion $gg \to h_2$ can be larger than that for the would-be SM Higgs boson with mass M_2. Than the process $gg \to h_2 \to h_1 h_1$ can be seen as resonant production of $h_1 h_1$ pair. In principle, it allows to discover the mentioned h_2 at LHC, for special sets of parameters).