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Triple Higgs coupling in the most general 2HDM at SM-like scenario

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Abstract We consider the triple Higgs coupling for $h(125)$ Higgs boson within the most general 2HDM. At moderate values of parameters of model, allowing by modern data, noticeable deviation of this coupling from its SM value is improbable. This deviation can be sizable only if some measurable parameters of the model are exotic.

1 Introduction

The recent discovery of a Higgs boson with $M \approx 125$ GeV at the LHC [1–6] suggests that the spontaneous electroweak symmetry breaking is most probably brought about by the Higgs mechanism. The simplest realization of the Higgs mechanism introduces a single scalar isodoublet ϕ with the Higgs potential $V_H = -m^2(\phi^\dagger\phi)/2 + \lambda(\phi^\dagger\phi)^2/2$. This model is usually called the Standard Model (SM).

The mentioned data do not rule out the possibility of realization of *beyond SM models* (BSM) which include both neutral Higgs scalars h_a (generally without definite CP parity) and charged Higgs scalars $H_b^\pm$ with masses M_a and $M_{b\pm}$, respectively.

In the discussion that follows we use the relative couplings for each neutral Higgs boson h_a (for the case with single charged Higgs boson $H^\pm$):

$$\chi_a^P = \frac{g_a^P}{g_{\rm SM}^P} \quad [P = V\,(W,Z),\ q = t, b, \dots,\ \ell = \tau, \dots],$$
$$\chi_a^\pm = \frac{g(H^+H^-h_a)}{2M_\pm^2/v}, \quad \chi_a^{H^+W^-} = \frac{g(H^+W^-h_a)}{M_W/v},$$
$$\chi_{abc} = \frac{g(h_a h_b h_c)}{g(hhh)_{SM}}. \tag{1}$$

The quantities χ_a^P are the ratios of the couplings of h_a with the fundamental particles P to the corresponding couplings for the would-be SM Higgs boson with $M_h = M_a$. The other relative couplings describe the interaction of h_a with a charged Higgs boson. The couplings χ_a^V and $\chi_a^\pm$ are real due to the Hermiticity of the Lagrangian, while the other couplings are generally complex.

We omit the adjective "relative" below.

1.1 SM-like scenario

Current data allow us to suggest that Nature realizes an *SM-like scenario*[1]: *The observed particle with mass* $M \approx 125$ GeV is a Higgs boson, and we denote it h_1. It interacts with the gauge bosons and t-quarks with coupling strengths that are close to those predicted by the SM within experimental accuracy (see e.g. [7–10]). In particular, for coupling with the gauge bosons

$$\varepsilon_V = |1 - (\chi_1^V)^2| \ll 1. \tag{2}$$

In the estimates we have in mind $\varepsilon_V \le 0.1$.

1.2 Two Higgs doublet model (2HDM)

The 2HDM presents the simplest extension of the standard Higgs model [22]. It offers a number of phenomenological scenarios with different physical contents in different regions of the model parameter space, such as a natural mechanism for spontaneous CP violation, etc. [22–24] For example, the Higgs sector of the MSSM is a particular case of 2HDM. Some variants of 2HDM have interesting cosmological consequences [25,26].

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[1] The term *SM-like scenario* was introduced in [11–18], the term *alignment limit* was introduced recently for this very situation, see e.g. [19–21], the *decoupling limit* is the particular case of this scenario.

In the most general 2HDM the couplings (1) obey the following sum rules [27–30]:

$$\sum_a (\chi_a^V)^2 = 1, \tag{3a}$$

$$|\chi_a^V|^2 + |\chi_a^{H^\pm W^\mp}|^2 = 1, \tag{3b}$$

$$\sum_a (\chi_a^f)^2 = 1. \tag{3c}$$

We have constructed in [30] the minimal complete set of measurable quantities ("observables") which determine all parameters of the 2HDM. This set contains

$$\begin{aligned}
&\text{v.e.v. of Higgs field } v = 246\text{ GeV},\\
&\text{masses of Higgs bosons } M_a,\ M_\pm\ (a=1,2,3),\\
&\text{two out of three couplings } \chi_a^V,\\
&3 \text{ couplings } H^+H^-h_a \ (\text{quantities } \chi_a^\pm \text{ Eq. (1)}),\\
&\text{quartic coupling } g(H^+H^-H^+H^-).
\end{aligned} \tag{4}$$

In the most general 2HDM, these observables are independent of each other. In some particular variants of 2HDM, additional relations between these parameters may appear (for example, in the CP-conserving case we have $\chi_3^V = 0$, $\chi_3^\pm = 0$).

1.3 Limitations for parameters

The values of parameters λ_a of 2HDM (and therefore the mentioned basic parameters) obey two groups of constraints (see e.g. [23,24]).

Positivity constraints are conditions for the stability of Higgs potential at large quasi-classical values of fields. They do not restrict the parameters from above.

Perturbativity (and unitarity) constraints make it possible to use the first non-vanishing approximation of perturbation theory for description of physical phenomena with reasonable accuracy – a *perturbative description*. (This is a tree approximation for most of the phenomena and a one-loop approximation for the phenomena which are absent at tree level, e.g. decays $h \to \gamma\gamma$, $h \to Z\gamma$, $h \to gg$.) The starting point in obtaining of these constraints is the observation that the effective parameter of the perturbative expansion is not λ_i $(i = 1, 2, \dots 7)$ but λ_i/Δ with $\Delta = 8\pi$ or 4π. The perturbativity condition is written usually in the form $|\lambda_i| < \Delta$.

At $|\lambda_i| \approx \Delta$ a perturbative description of the physical phenomena is incorrect even at low energies. In particular, the equations, expressing masses and couplings via the parameters of the Lagrangian, become invalid. Good examples provide the one-loop radiative corrections (RC) to the triple Higgs coupling [31–38]. In the SM-like scenario these RC reach $150 \div 200\%$ at $|\lambda_i| \approx \Delta$. (Reference [38] presents an example with clear details. The authors consider the Inert Doublet Model, i.e. 2HDM with exact Z_2 symmetry in the SM-like case, at $\lambda_4 = \lambda_5 = 0$ and $\lambda_1 = \lambda_{SM}$. The one-loop corrections to $g(h_1h_1h_1)$ are described by the single parameter λ_3, and they reach 180% at $|\lambda_3| \approx \Delta$.)

The first non-vanishing approximation of perturbation theory describes physical phenomena with relative inaccuracy k only at

$$|\lambda_i| < k\Delta \qquad (k < 1). \tag{5}$$

In particular, in the region of the parameters, the provided accuracy of the standard description in 30% one should have $k = 0.3$. In this region of parameters the value of RC, discussed in [31–38], does not exceed 20%.

Below we will have in mind this very limitation with $k \approx 0.3$.

The realization of the SM-like scenario imposes additional restrictions on the parameters. Because of the sum rules (3), in the SM-like scenario the couplings of the other neutrals h_a with gauge bosons χ_a^V are small. Besides, the absolute value of the non-diagonal coupling with EW gauge bosons for the observed Higgs boson $\chi_1^{W^\pm H^\mp}$ is small,[2] while similar couplings for the other neutrals $\chi_{2,3}^{W^\pm H^\mp}$ are close to their maximal possible values:

$$\boxed{(3a)} \;\Rightarrow\; |\chi_a^V|^2 < \varepsilon_V \ll 1, \quad a = 2, 3, \tag{6}$$

$$\boxed{(3b)} \;\Rightarrow\; |\chi_1^{H^\pm W^\mp}|^2 \sim \varepsilon_V \ll 1; \quad |\chi_{2,3}^{H^\pm W^\mp}|^2 \approx 1. \tag{7}$$

In the SM-like scenario the perturbativity constraints lead to additional restrictions. In particular, according to Eq. (23) from Ref. [30], the perturbativity constraint (5) imposes the limitation on the coupling of h_1 to charged Higgs bosons:

$$|\chi_1^\pm| < 1 \;\text{ at }\; M_\pm > 500\text{ GeV}. \tag{8}$$

It means that the heavy charged Higgs boson gives only a small contribution to the two-photon width of the observed Higgs boson h_1.

Next, we consider heavy neutral Higgs bosons h_a $(a = 2, 3)$ in the SM-like scenario. The couplings χ_a^V are small (see (6)), while Eq. (23) from Ref. [30] allows us to have big values of $\chi_a^\pm$ $(\lesssim 1/\sqrt{\varepsilon_V})$. Therefore, the two-photon width of the boson h_a is strongly different from a similar width as calculated for the would-be SM Higgs boson with the mass M_a.

The last statement is illustrated by a simple calculation for the toy case $M_2 = 600$ GeV, $M_\pm = 300$ GeV. We present in the table the total Higgs width Γ_{tot} in GeV, and its two-photon width $\Gamma(\gamma\gamma)$ in MeV for different scenarios, assuming the partial width $h_2 \to h_1h_1$ to be small.

[2] The calculations of $H^- \to W^-h_1$ decay at LHC in [66,67] are made in the CP-conserving 2HDM and with not very small ε_V.

Scenario	Γ_{tot}	$\Gamma(\gamma\gamma)$	$\mathrm{Br}(\gamma\gamma)$
Would-be SM	114	1	0.9×10^{-5}
$\chi_2^V=0.1$, $\chi_2^t=0.3$, $\chi_2^\pm=0$	2.65	0.042	1.6×10^{-5}
$\chi_2^V=0.1$, $\chi_2^t=0.3$, $\chi_2^\pm=1$	2.65	0.1	3.7×10^{-5}
$\chi_2^V=0.1$, $\chi_2^t=0.3$, $\chi_2^\pm=2$	2.65	0.27	10^{-4}
$\chi_2^V=0.1$, $\chi_2^t=1$, $\chi_2^\pm=0$	20.4	0.33	1.5×10^{-5}
$\chi_2^V=0.1$, $\chi_2^t=1$, $\chi_2^\pm=1$	20.4	0.66	3×10^{-5}
$\chi_2^V=0.1$, $\chi_2^t=1$, $\chi_2^\pm=2$	20.4	1.05	5×10^{-5}

2 Triple Higgs vertex

The observation of hh production and the extraction of the triple Higgs vertex $g(hhh)$ from the future experiments is scheduled at the LHC and other colliders. This is a necessary step in the verification of the Higgs mechanism. Hopefully, these observations will allow us to see the effects of BSM.[3]

The studies of triple Higgs coupling have long history; for recent reviews see e.g. [39–42]. There are two major problems. The first one is whether it is possible or not to observe hh production, caused by hhh vertex. The second one is whether it is possible to use these observations for the extraction of New Physics effects beyond SM.

The accuracy in the extraction of a triple Higgs vertex $g(hhh)$ from the future data cannot be high, since in each case the corresponding experiments deal with interference of two channels – an independent production of two Higgses and production of Higgses via hhh vertex. This interference is mainly destructive [43,44]. For example, for a 100 TeV hadron collider with total luminosity $3/ab$ one can hope to reach an accuracy of 40% in the extraction of this vertex from future data [45–48]; at ILC the accuracy in the extraction of $g(hhh)$ will be better than 80% only after 10 years of operation [49]. Therefore, the effects of New Physics will be distinguishable in the data of $g(hhh)$ in the realistic future only if the deviation of this coupling from its SM value is high enough,

$$|\chi_{111}-1|\gtrsim 1. \tag{9}$$

One of the approaches in the description of the SM violations is to add in the SM Lagrangian terms with anomalous interactions of Higgs boson. It was found for many reasonable benchmark points that these anomalous interactions are difficult to observe [50–54].

The other approach is to consider some special form of BSM. The review of the whole variety of possible BSM models is beyond our scope. We limit ourself to a consideration of 2HDM in its most general form.

The potential of such a $g(h_1h_1h_1)$ observation was studied for some benchmark points of the parameters of 2HDM mainly in the case of CP conservation and with moderate values of the parameters [55–60], for the MSSM with CP conservation [61,62] or with violated CP [63,64] mainly beyond the SM-like scenario. The case of the SM-like scenario with similar limitations was considered in [65].

2.1 Triple Higgs coupling via observables

The transition from neutral components of basic fields $\phi_{1,2}$ to the neutral Higgs bosons h_a is described by some mixing matrix. The equation for triple Higgs coupling in the most general 2HDM via the parameters of the Lagrangian and elements of this mixing matrix is obtained simply (see e.g. Eq. (25) of Ref. [30]). The expression of this coupling in terms of the introduced observables (4) was obtained in Eq. (36) of Ref. [30]. We transform it to the following form:

$$\begin{aligned}
&g(h_1h_1h_1)=(M_1^2/v)\,\chi_{111};\\
&\chi_{111}=\chi_1^V\left[1+\left(1-(\chi_1^V)^2\right)R\right],\quad R=\sum_{i=1}^{3}R_i;\\
&R_1=\frac{2M_\pm^2}{M_1^2}\left(\chi_1^V\chi_1^\pm-1\right),\quad R_2=1+2\sum_{b=1}^{3}\frac{M_b^2}{M_1^2}(\chi_b^V)^2,\\
&R_3=\frac{2M_\pm^2}{M_1^2}\left[\sum_{b=2}^{3}\chi_b^V\chi_b^\pm+Re\left(\frac{\chi_1^{H^-W^+}}{\chi_1^V}\sum_{b=1}^{3}\chi_b^{H^+W^-}\chi_b^\pm\right)\right].
\end{aligned} \tag{10}$$

2.2 Triple Higgs coupling in SM-like scenario

With the estimates (6), (7) we have

$$\chi_{111}\approx[1+(R-1/2)\varepsilon_V]. \tag{11}$$

We see that at moderate values of the parameters, the relative coupling χ_{111} is close to 1, and it is difficult to expect a sizable effect.[4]

Nevertheless, it is interesting to consider the *special exotic values of the model parameters* that provide sizable deviations of the triple Higgs coupling from its SM value, i.e. $|\chi_{111}-1|\gtrsim 1$. We consider the effect of different terms R_i, entering R.

The term R_1 can give $|\chi_{111}-1|\gtrsim 1$ if the charged Higgs boson $H^\pm$ is heavy enough and the coupling $\chi_1^\pm$ of the observed Higgs boson with $H^\pm$ deviates substantially from

[3] In the models containing additional heavy Higgs bosons h_a with $M_a>2M_1$, the **resonant** h_1h_1 production like $pp\to(h_2\to h_1h_1)+\cdots$ becomes possible. In this paper we discuss only non-resonant h_1h_1 production, without intermediate $h_a\neq h_1$.

[4] For the particular CP-conserving case and with moderate values of parameters such a conclusion was obtained in [55–60,65] (see also [61–64] for the CP-conserving MSSM).

the value $\chi_1^{\pm} \approx 1$. In view of Eq. (8), it can happen if this coupling is either very small or negative.

The term $R_2 \sim 3+\varepsilon_V(M_b^2/M_1^2)$ can give $|\chi_{111}-1| \gtrsim 1$ only if at least one of the other Higgs bosons $h_{2,3}$ is heavy enough, $M_{2,3} > 1$ TeV. Direct discovery of such Higgs bosons seems to be a difficult task. Therefore the value of $g(h_1h_1h_1)$ might become an important source of knowledge as regards such heavy neutrals for a long time.

The term R_3 contains small factors $\chi_{2,3}^V$, $\chi_1^{H^+W^-}$ and factors $\chi_{2,3}^{\pm}$ which can be large (up to $1/\sqrt{\varepsilon_V}$). The term R_3 may not be small if $H^{\pm}$ is heavy.

Certainly, the real range of possible values of discussed parameters is restricted by other observations. Better estimates are possible only after measuring of ε_V with reasonable accuracy. In particular, at $\varepsilon_V \ll 0.1$ we cannot expect sizable effects in the triple Higgs vertex.

3 Summary

- Measuring hh production at various colliders is a necessary step in the verification of the Higgs mechanism of EWSB. Within the SM-like scenario in the 2HDM, these measurements can give information as regards New Physics beyond SM only at exotic values of the parameters listed above. The enlargement of the field of parameters of 2HDM at the transition from CP-conserved softly Z_2 broken potential to the most general case gives no new essential opportunities in the deviation of triple Higgs coupling from its SM value.
  In our conclusions we limit ourselves to perturbative limitations in the form (5) with $k \sim 0.3$. These limitations guarantee us applicability of first orders of perturbation theory for a description of model (including the expressions of the masses and couplings via the parameters of the Lagrangian) and a small value of the quantum (loop) corrections.
- In other models the deviation of the triple Higgs coupling from its SM value can be stronger than that in 2HDM at moderate values of the parameters; see [68,69]. In the particular case of the nMSSM (2HDM +Higgs singlet) values χ_{111} can range from -5 to 20 [61–64].
- If the mass M_2 of the heavier Higgs boson h_2 lies within the interval (250÷400) GeV and $|\chi_2^t| > 1$ (in the SM-like scenario for h_1), the following interesting phenomenon takes place. The boson h_2 becomes 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. The process $gg \to h_2 \to h_1h_1$ can be seen as a resonant production of the h_1h_1 pair. In principle, it allows us to discover the mentioned h_2 at LHC (see the examples in [55–60,70,71] for special sets of parameters).

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