Standard-Model-like scenarios in the 2HDM and Photon Collider potential

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Abstract. After operations at the LHC and $e^+e^-$ Linear Colliders it may be found that a Standard-Model-like scenario is realized. In this scenario no new particle will be discovered, except a single Higgs boson having partial widths or coupling constants with fundamental particles, whose squares are close, within anticipated experimental uncertainty, to those of the SM. Experiments at a Photon Collider can resolve whether the SM or e.g. the Two-Higgs-Doublet Model is realized in Nature.

For the SM-like realizations of the 2HDM (II) we study the loop couplings of the Higgs boson with $\gamma\gamma$ and $Z\gamma$, and also with gluons. The deviation of the two-photon width from its SM value is generally higher than the expected inaccuracy in the measurement of $\Gamma_{\gamma\gamma}$ at a Photon Collider. The deviation is sensitive to the parameters of the Higgs self interaction.

I INTRODUCTION. SM-LIKE SCENARIO

It could happen that no new particles will be discovered at the Tevatron, the LHC and $e^+e^-$ Linear Colliders [1] except the SM-like Higgs boson. In this case the main task for new colliders will be to search for signals of new physics via deviations of observed quantities from Standard-Model predictions. The study of Higgs boson production at a Photon Collider [2] offers excellent opportunities for this [3]. Indeed, in the SM and in its extensions, all fundamental charged particles contribute to the $h\gamma\gamma$ and $hZ\gamma$ effective couplings. Besides, these couplings are absent in the SM at tree level, appearing only at the loop level. Therefore, the background for signals of new physics will be relatively lower here than in processes which are allowed at tree level of the SM.

We assume [4] that an SM-like scenario is realized, i.e., the Higgs particle has been found at the Tevatron or the LHC and its partial widths or coupling constants squared are precisely measured (mainly at the $e^+e^-$ Linear Collider), being in agreement with those of the SM, within the anticipated experimental accuracies. This can happen not only in the SM, but also if Nature is described by some other theory, for example, the Two-Higgs-Doublet Model (2HDM) or the Minimal
Supersymmetric Standard Model (MSSM). Here we compare the SM and the SM-like scenario in the 2HDM (II).

The **SM-like scenario** can be defined by the following criteria:

- One Higgs boson will be discovered with mass above today’s limit for an SM Higgs boson, 115 GeV [5]. This can be either the Higgs boson of the SM or one neutral Higgs boson from some other model.

- No other Higgs boson will be discovered. Any other Higgs boson is weakly coupled with the $Z$ boson, gluons and quarks, or sufficiently heavy to escape observation: $M_H, M_A, M_{H^\pm} > \mathcal{O}(800 \text{ GeV})$ [6].

- Any other new particle that may exist is beyond the discovery limits of LHC and the $e^+e^-$ Linear Collider.

- The measured decay widths of this Higgs boson (or coupling constants squared) to quarks, charged leptons, electroweak gauge bosons and gluons, $\Gamma^\text{exp}_i (i = q, l, W, Z, g)$, will be in agreement with their SM values $\Gamma^\text{SM}_i$ within the experimental precision, $|\Gamma^\text{exp}_i/\Gamma^\text{SM}_i - 1| \ll 1$.

II  
**PRECISION OF MEASURED SM HIGGS COUPLINGS**

At the TESLA $e^+e^-$ collider the discussed production cross sections are expected to be measured with a significantly higher precision than at the LHC [6]. At $M_h = 120$ GeV, with integrated luminosity 500 fb$^{-1}$ one can expect for the basic couplings the following relative accuracy [7]:

$$\delta_b = 0.021, \quad \delta_t = 0.022, \quad \delta_{W/Z} = 0.012. \quad (1)$$

Experiments at Photon Colliders open new perspectives. Even with a modest integrated luminosity of a $\gamma\gamma$ collider in the high energy peak of about 40 fb$^{-1}$, a $\gamma\gamma$ collider makes it possible to obtain the accuracy in measuring $h\gamma\gamma$ [8]:

$$\delta_\gamma = 0.02 \quad \text{for } M_h < 140 \text{ GeV}, \quad (2)$$

to be compared to 13% at a linear collider at 500 fb$^{-1}$ [7,9]. The accuracy in the measurement of the effective $hZ\gamma$ ($HZ\gamma$) coupling in the process $e\gamma \rightarrow eh$ ($e\gamma \rightarrow eH$) is lower.

We will use the above uncertainties to constrain ratios of actual (in principle measurable) coupling constants of each neutral Higgs scalar $\phi$ ($h$ or $H$) of the 2HDM (II) in the SM-like realizations¹ with particle $i$ to the corresponding value for the Higgs boson in the SM,

1) Discussing both these scalars, we use the notation $\phi$ for $h$ and $H$. 

\[ \chi_i^\phi = \frac{g_{\phi i}^i}{g_{\text{SM}}}, \quad \text{where} \quad \chi_i^\phi = \pm (1 - \epsilon_i), \quad \text{with} \quad |\epsilon_i| \ll 1. \] (3)

The allowed ranges for \( \epsilon_i \) are constrained by the experimental accuracies \( \delta_i \), \( |\epsilon_i| \leq \delta_i \). Additional constraints follow from the structure of the considered model.

### III TWO-HIGGS-DOUBLET MODEL (II)

We here consider the CP-conserving Two-Higgs-Doublet Model in its Model II implementation, denoted by 2HDM (II) [10–12]. Here, one doublet of fundamental scalar fields couples to \( u \)-type quarks, the other to \( d \)-type quarks and charged leptons. The Higgs sector contains three neutral Higgs particles, two CP-even scalars \( h \) and \( H \), one CP-odd (pseudoscalar) \( A \), and charged Higgs bosons \( H^\pm \) — it coincides in the 2HDM (II) and in the MSSM.

In the SM-like scenario realized in the 2HDM we need to consider both possibilities: not only the light scalar Higgs boson, \( h \), but also the heavier one, \( H \), could imitate the SM Higgs boson if the lighter scalar \( h \) escapes detection [13,14].

The ratios of the direct coupling constants of the Higgs bosons \( \phi = h, H \) to the gauge bosons \( V = W \text{ or } Z \) bosons, to up and down quarks and to charged leptons, relative to their SM values can be expressed via angles \( \alpha \) and \( \beta \) [10,12]:

\[ \begin{align*}
\chi_V^\phi &= \sin(\beta - \alpha + \delta_\phi), \\
\chi_u^\phi &= \sin(\beta - \alpha + \delta_\phi) + \cot \beta \cos(\beta - \alpha + \delta_\phi), \\
\chi_d^\phi &= \sin(\beta - \alpha + \delta_\phi) - \tan \beta \cos(\beta - \alpha + \delta_\phi), \\
\delta_h &= 0, \quad \delta_H = \frac{\pi}{2}.
\end{align*} \] (4)

Here, \( \beta \in (0, \pi/2) \) parameterizes the ratio of the vacuum expectation values of the two basic Higgs doublets and \( \alpha \in (-\pi, 0) \) parameterizes mixing among the two neutral CP-even Higgs fields.

The coupling of the charged Higgs boson to the neutral scalars \( \phi \) depends on the Higgs-boson masses and on the additional parameter \( \lambda_5 \) (compare [10,15], note that the paper [12] uses another parameterization of the 2HDM)

\[ \chi_{H^\pm}^\phi = \left(1 - \frac{M_\phi^2}{2M_{H^\pm}^2}\right)\chi_V^\phi + \left(\frac{M_\phi^2}{2M_{H^\pm}^2} - \frac{\lambda_5}{2\lambda_4}\right)(\chi_u^\phi + \chi_d^\phi), \quad \lambda_4 = \frac{2M_{H^\pm}^2}{v^2}. \] (5)

### IV PATTERN RELATION AND ALLOWED RANGES FOR COUPLINGS

The quantities \( \chi_i^\phi \) for the couplings (4) of each scalar (referred to below as basic couplings) are closely related to the observables and it is more natural to use them, instead of \( \alpha \) and \( \beta \). Since for each \( \phi \) these three \( \chi_i \) can be expressed in terms of two angles, they fulfill a simple relation (pattern relation), which plays a basic role
in our analysis (it is valid in the MSSM as well). It has the same form for both \(h\) and \(H\), namely \((\chi_u - \chi_V)(\chi_V - \chi_d) + \chi_V^2 = 1\), or
\[
(\chi_u + \chi_d)\chi_V = 1 + \chi_u\chi_d.
\]

(6)

Furthermore, from Eq. (4) follows the condition: \(\tan^2 \beta = (\chi_V - \chi_d)/(\chi_u - \chi_V) = (1 - \chi_d^2)/(\chi_u^2 - 1)\).

In the following discussion we will assume only one value for each up-type quark, down-type quark, charged lepton and gauge boson coupling with the Higgs boson, in numerical calculation we will use the best estimate for each category, e.g. \(\delta_b\) for \(\delta_d\). The SM-like scenario means, in particular, that \(\chi_i^2 \approx 1\) for the basic couplings. We consider solutions of the equations (3) constrained by the pattern relation (6).

These solutions can be further classified as follows. For solutions \(A_{\phi \pm}\) the relative couplings are approximately identical, \(\chi_V \approx \chi_u \approx \chi_d \approx \pm 1\). There are also solutions \(B_{\phi \pm q}\), where some of the \(\chi_i \approx 1\) but other \(\chi_j \approx -1\). Here, the first subscript labels the observed Higgs boson (\(\phi = h, H\)). The second subscript \(\pm\) labels the sign of \(\chi_{\phi V}\). The third subscript \(q = d, u\) (only for solutions \(B\)) labels the quark whose coupling constant to the Higgs boson is opposite to that of the vector boson. Our analysis [4] shows that an SM-like scenario can be realized for only a limited part of the 2HDM parameter space, summarized in Table 1.

| observed Higgs boson | \(\chi_V\) | \(\tan \beta\) | constraint |
|---------------------|-----------|-----------|-----------|
| \(A_{\phi \pm}\)    | \(h\)     | \(\approx +1\) | \(> 1\)   | \(\epsilon_V = -\frac{\epsilon_V \epsilon_d}{2}\) |
| \(\chi_V \approx \chi_u \approx \chi_d\) | \(h\)     | \(\approx -1\) | \(\sqrt{|\epsilon_V|} > 1\) | \(\epsilon_u = -\frac{\epsilon_u \epsilon_d}{2}\) |
| \(H\)               | \(\approx -1\) | \(< 1\)   |           |
| \(B_{\phi \pm d}\)  | \(h\)     | \(\approx +1\) | \(\sqrt{2/\epsilon_V} > 1\) | \(\epsilon_u = -\frac{\epsilon_u \epsilon_d}{2}\) |
| \(\chi_V \approx \chi_u \approx -\chi_d\) | \(h\)     | \(\approx -1\) | \(\sqrt{2/\epsilon_V} > 1\) | \(\epsilon_u = -\frac{\epsilon_u \epsilon_d}{2}\) |
| \(H\)               | \(\approx -1\) | \(< 1\)   |           |
| \(B_{h+u}\)         | \(h\)     | \(\approx +1\) | \(\sqrt{2/\epsilon_V} < 1\) | \(\epsilon_d = -\frac{\epsilon_u \epsilon_d}{2}\) |
| \(\chi_V \approx \chi_d \approx -\chi_u\) | \(h\)     | \(\approx +1\) | \(\sqrt{2/\epsilon_V} < 1\) | \(\epsilon_d = -\frac{\epsilon_u \epsilon_d}{2}\) |

\(\chi_i = \frac{g_i}{g_{g^\prime}} = \pm(1 - \epsilon_i)\) with 
\(i = V(\equiv Z, W)\) or \(i = u(\equiv t, c)\) or \(i = d, \ell(\equiv b, \tau)\).
\(\epsilon_V > 0, \epsilon_u, \epsilon_d < 0\)

**TABLE 1.** Realizations of SM-like scenario in the 2HDM (II).
V DISTINGUISHING MODELS VIA LOOP COUPLINGS

In order to distinguish models in the considered SM-like scenario, we compute loop-induced couplings of the Higgs boson with photons or gluons [10,15] for these solutions $A$ and $B$ within the ranges of the coupling constants allowed by the anticipated experimental inaccuracies from Eq. (1). To estimate the deviation from the SM, we consider the ratios of widths $|\chi_{\gamma\gamma}|^2$ and $|\chi_{Z\gamma}|^2$ obtained in the 2HDM (II) and in the SM. In the 2HDM the couplings with photons, $\phi\gamma\gamma$ and $\phi Z\gamma$, contain contributions from fermions, and from the charged gauge boson $W^{\pm}$, like in the SM. In addition, there are contributions from the charged Higgs boson, $H^{\pm}$. For definiteness, we perform all calculations for $M_{H^{\pm}} = 800$ GeV. At $M_\phi < 250$ GeV the contribution of the charged Higgs boson loop varies by less than 5% when $M_{H^{\pm}}$ varies from 800 GeV to infinity. We have kept track of all relevant couplings to make sure they are in the perturbative regime for observed Higgs boson masses up to 3 TeV. If the SM-like Higgs is $h$ then any non-perturbative coupling would correspond to the unobserved Higgs boson $H$.

The $\gamma\gamma$ width looks the most promising one for distinguishing models.

Solutions A. A new feature of the two-photon width, as compared to the SM case, is the contribution due to the charged Higgs boson loops. It is known that the scalar loop contribution to the photonic widths is less than that of fermion and $W$ boson loops (the last is the largest). The contributions of $W$ and $t$-quark loops are of opposite sign, i.e., they partially compensate each other, thus, the effect of scalar loops is enhanced here. The coupling $\chi_{H^{\pm}}$ depends on $\lambda_5$, which is not fixed by the observable masses. This dependence is linear:

$$|\chi_{\gamma\gamma}|^2 = \frac{\Gamma^{2HDM}_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = 1 - R_{\gamma\gamma} \left(1 - \frac{\lambda_5}{\lambda_4}\right)$$

with a similar dependence for the $Z\gamma$ decay.

For the solutions $B$ the coupling of the charged Higgs boson $H^{\pm}$ to the observed neutral one, $\chi_{H^{\pm}}$, is practically independent of $\lambda_5$ since $\chi_d + \chi_u \approx 0$. Also, if the charged Higgs boson $H^{\pm}$ is heavy (as is the case in the SM-like scenario), its coupling to the neutral Higgs scalars $\phi$ is close to that of the vector bosons, $\chi_{H^{\pm}} \approx \chi_V$. For solutions $B_{\phi\pm d}$ the main difference in the two-photon width from that of the SM is given by the contribution of charged Higgs bosons, for the solution $B_{h+u}$ also in the change of sign of the coupling to the $t$-quark as compared to the SM case.

In Fig. 1 we show the ratio of the two-photon Higgs widths to the SM value for the solutions $A$ (left) and $B$ (right). For the solutions $A$ these curves correspond to the case $\lambda_5 = 0$. Solid curves correspond to the “exact” case with $|\chi_i| = 1$, for $i = q, W/Z$. As discussed above, these curves are below unity due to the contribution of the charged Higgs boson, and for the solution $B_{h+u}$, also due to the “wrong” sign of the $huu$ (or $htt$) coupling. The shaded bands are derived from
the anticipated 1 σ bounds around the SM values of two measured basic coupling constants: for the solution $A$ for $g_d$ and $g_u$, for solution $B_{h \pm d}$ ($B_{h+u}$) for $g_Z$ and $g_d$ ($g_u$). The third basic coupling is, by virtue of the pattern equation, much closer to the SM value than the corresponding anticipated error for this quantity.

FIGURE 1. Ratios of the Higgs boson $\phi \rightarrow \gamma \gamma$ decay width in the 2HDM and the SM as functions of $M_{h,H}$ for all solutions $A$ (with $\lambda_5 = 0$) and $B$. The shaded bands correspond to the uncertainties expected at 120 GeV. At masses above 140 GeV, a more detailed analysis is required.

In Table 2 we present values for these ratios, and for comparison also for $Z\gamma$ and $gg$, for $M_\phi = 120$ GeV, and for the “exact” case ($|\chi_i| = 1$).

| solution | basic couplings | SM-like realization | $|\chi_{Z\gamma}|^2$ | $|\chi_{gg}|^2$ | $|\chi_{h\gamma}|^2$ |
|----------|----------------|---------------------|---------------------|------------------|------------------|
| $A_{\phi \pm}$ | $\chi_V \approx \chi_d \approx \chi_u \approx \pm 1$ | $A_{h \pm}$; $A_{H-}$ | 0.90 | 0.96 | 1.00 |
| $B_{\phi \pm d}$ | $\chi_V \approx -\chi_d \approx \chi_u \approx \pm 1$ | $B_{h \pm d}$; $B_{H-d}$ | 0.87 | 0.96 | 1.28 |
| $B_{\phi \pm u}$ | $\chi_V \approx \chi_d \approx -\chi_u \approx \pm 1$ | $B_{h+u}$ | 2.28 | 1.21 | 1.28 |

TABLE 2. Summary of the solutions and SM-like realizations. The last three columns give ratios of loop-induced partial widths to their SM values at $M_\phi = 120$ GeV for the SM-like scenarios in the 2HDM (II) in the “exact” case ($|\chi_i| = 1$). The quantities for solutions $A$ depend on $\lambda_5$; here $\lambda_5 = 0$.

The deviation from unity is large enough to allow a reliable distinction of the 2HDM from the SM in the process $\gamma \gamma \rightarrow h, H$. This conclusion is valid in a wide range of $\lambda_5$ values. The possible precision in the determination of $\lambda_5$ from the two-photon width depends on the mass of the charged Higgs boson. The deviations of the $\phi Z\gamma$ width from its SM value was found to be lower than that of the two photon width, see Table 2.
The two-gluon width is determined by the contributions of $t$ and $b$ quarks. For not too high values of $\tan \beta$, the $t$-quark contribution dominates. So, the difference $\chi_{gg} - 1$ is determined by the difference $\chi_u - 1$, and with high accuracy $\chi_{gg} - 1 \approx 2(\chi_u - 1)$. If $\tan \beta \ll 1$ then the deviation of the Higgs boson coupling with $t$-quark from its SM value can for solutions $B$ be large compared to the expected experimental uncertainty $1$, see Table 2. In this case the two-gluon width can differ from its SM value by more than the expected experimental uncertainty (5.5% at the Linear Collider), and the measurement of the two-gluon width could exclude the SM-like scenario from being realized by the 2HDM. In such a case the Photon Collider can be used for a more detailed study of the realized non-standard Higgs sector.

VI CONCLUSION

An SM-like scenario observed at the LHC and $e^+e^-$ Linear Colliders can occur both in the SM and in other models, including the 2HDM (II). In order to distinguish these models, we implement a pattern relation among basic couplings which is valid in the 2HDM and in the MSSM. Taking into account anticipated uncertainties in future measurements of the basic couplings of the Higgs boson, we found that the considered SM-like scenario (in which partial widths of Higgs boson decay are close to their SM values) has three types of allowed realizations.

The comparison of the presented results for the two-photon width with the anticipated experimental uncertainty (2) shows that the deviation of the two-photon width ratio from unity is generally large enough to allow a reliable distinction of the 2HDM (II) from the SM at a Photon Collider. For the solutions $B$ this conclusion is valid for arbitrary values of $\lambda_5$ and arbitrary masses of other (unobserved) Higgs bosons. For the solutions $A$, according to Eq. (7), this conclusion is valid in a wide range of values $\lambda_5 \notin (\lambda_4 - \lambda_4\delta_\gamma/R_{\gamma\gamma}, \lambda_4 + \lambda_4\delta_\gamma/R_{\gamma\gamma})$ with $\lambda_4 = 2M_{H\pm}^2/v^2$. The possible precision in the determination of $\lambda_5/\lambda_4$ from the two-photon width depends strongly on the achieved precision in the determination of the $ht\bar{t}$ coupling.

These conclusions are accurate for a Higgs boson lighter than 140 GeV. A new analysis of experimental uncertainties is necessary if the observed Higgs boson will be heavier than 140 GeV. The measurement of the Higgs boson production in the process $e\gamma \rightarrow eh$, which is sensitive to the $hZ\gamma$ coupling, will be an additional test of the nature of the Higgs sector.

The obtained predictions are practically identical for the cases when the observed scalar is the lighter Higgs boson of 2HDM ($h$) or the heavier one ($H$).

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