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Distinguishing Higgs Models at Photon Colliders[a]

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We consider the two effective couplings $hZ\gamma$ and $h\gamma\gamma$ involving a neutral scalar Higgs boson with a mass around 100 GeV in the Standard Model, in the Two Higgs Doublet Model, and in the Minimal Supersymmetric Standard Model. The couplings can be tested at Photon Colliders, and used to distinguish these models.

1 Introduction

Many recent studies for the TEVATRON, LHC and HERA assume, in fact, that Nature is so favorable for us that new particles are sufficiently light that they can be seen at these facilities. We should like to discuss here the opposite scenario: *No new particles will be discovered at these facilities, except the Higgs scalar(s).*

In this scenario, additional particles could very well exist in addition to the Higgs boson, but they would have to be heavier than 1–2 TeV. What new physics is realized could then be revealed at an e^+e^- Linear Collider,[1] where the *direct* couplings of the Higgs boson with matter will be measured with high accuracy. Other couplings, which only occur at the one-loop level, like $h\gamma\gamma$ and $hZ\gamma$, can only be studied with higher statistics, and then only at lower accuracy. The importance of these couplings is related to the fact that in the SM and in its extensions, all fundamental charged particles are included in the loop, so the structure of the theory influences the corresponding Higgs boson decays. The $\gamma\gamma$ and γe modes of a Linear Collider (Photon Colliders)[2] provide an opportunity to measure these vertices with high enough accuracy, up to the

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2% level or better for the $\gamma\gamma$ mode[3] and up to a few percents for the $Z\gamma$ mode (reaction $e\gamma \to eH$). Therefore, the study of the Higgs boson production at Photon Colliders could distinguish different models of new physics prior to the discovery of other related new particles.

Frequently considered models going beyond the SM are the Two Higgs Doublet Model (2HDM), and the Minimal Supersymmetric Standard Model (MSSM). In the present paper we compare these loop-determined effective couplings $h\gamma\gamma$ and $hZ\gamma$, in the SM ($h = H_{\rm SM}$), in the 2HDM (Model II) where only the Higgs sector is enlarged compared to the SM, and in the MSSM, where the Higgs sector has formally the structure of Model II, but where the parameters are more constrained, and where, in addition, new supersymmetric particles appear. We study properties of the couplings of the Higgs bosons with photon(s) for the case when the mass of the lightest Higgs particle h in the 2HDM and the MSSM is in the region 100–130 GeV, which is still open for all three models.

These effective couplings are to a large extent determined by the couplings of the Higgs particle to the W, to the b and t quarks, and to the charged Higgs boson.[4] In terms of the parameters β (which parameterizes the ratio of the two vacuum expectation values) and α (which parameterizes the mixing among the two neutral, CP-even Higgs particles), these couplings are proportional to

$$\begin{aligned} g_{hWW} &\sim \sin(\beta-\alpha) \\ g_{hbb} &\sim -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \\ g_{htt} &\sim \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}, \end{aligned} \tag{1}$$

as compared with the SM couplings.

Within the scenario that no new physics, except the Higgs particle(s), is discovered at hadron or e^+e^- colliders, we can imagine two cases considered in the subsequent sections.

2 A light SM-like Higgs boson

The first studied opportunity is as follows. *All direct couplings are the same as in the SM with one Higgs doublet. How do we then determine whether the SM, the 2HDM or the MSSM is realized?* The answer can be obtained from a precise study of the two-photon Higgs width and the $hZ\gamma$ coupling at Photon Colliders, $\gamma\gamma$ and $e\gamma$,[2] where the current estimate of the accuracy in the measurement of the first width is of 2%.[3] Indeed, in the SM, these vertices are determined by contributions from W loops and matter loops, entering with opposite signs.[5] Because of this partial cancellation, the addition of new contributions could change these vertices significantly.

This situation can be realized in the 2HDM, with $\beta - \alpha = \pi/2$, leading to couplings to gauge bosons and fermions as in the SM (see above), and to some extent also in the MSSM. We have calculated the widths in these models for this case, as functions of $\tan\beta$, keeping for the 2HDM $\sin(\beta - \alpha) = 1$. However, the MSSM with given M_h and $\beta - \alpha$ values can be realized only at some definite value of β (if masses of heavy squarks are roughly fixed), see Fig. 1.

For the 2HDM, the difference with respect to the SM is in this case determined by the charged Higgs boson contribution only. The relevant quantity becomes in this case $b = 1 + (M_h^2 - \lambda_5 v^2)/(2M_{H^\pm}^2)$.[6] In the calculation for the general 2HDM(II) we assume $\lambda_5 v^2 \ll M_h^2$. This effect of the scalar loop is enhanced here due to the partial compensation of the W and t-quark contributions. The result is evidently independent of the mixing angle β. We find, for very heavy $H^\pm$ and M_h=100 GeV:

$$\Gamma_{h\gamma\gamma}^{\rm 2HDM}/\Gamma_{h\gamma\gamma}^{\rm SM} = 0.89, \qquad \Gamma_{hZ\gamma}^{\rm 2HDM}/\Gamma_{hZ\gamma}^{\rm SM} = 0.96. \tag{2}$$

The effect is of the order of about 10%—a difference large enough to be observed. With growth of λ_5 this effect decreases roughly as $(1 - \lambda_5 v^2/2M_{H^\pm}^2)$.

In the MSSM we encounter two differences. First, with a fixed mass of the lightest Higgs particle, only a finite range of $\tan\beta$ is physical. Throughout this range, the coupling of the lightest Higgs particle to the W will vary as $\sin(\beta - \alpha)$, which is uniquely determined by $\tan\beta$ and the Higgs mass. Since this loop contribution dominates the effective couplings under consideration, there will be a corresponding strong variation with $\tan\beta$, as illustrated in Fig. 1. Second, the contributions of the many superpartners depend on their masses. If all these masses are sufficiently heavy, the effects become small.[7]

3 Non-SM-like Higgs boson(s)

The second possibility is that the couplings with matter differ from those of the SM. In this case it is very likely that this fact is known from earlier measurements, and our goal will be to search for an opportunity to distinguish the cases of the 2HDM (II) and the MSSM. In this respect we note that the measurements at a Linear Collider will give us the couplings of the lightest Higgs boson with ordinary matter and, perhaps, masses of some of the more heavy Higgs particles. For a fixed mass M_h, the $h\gamma\gamma$ and $hZ\gamma$ couplings are much smaller in the 2HDM than in the MSSM, for a wide range of $\tan\beta$ values.

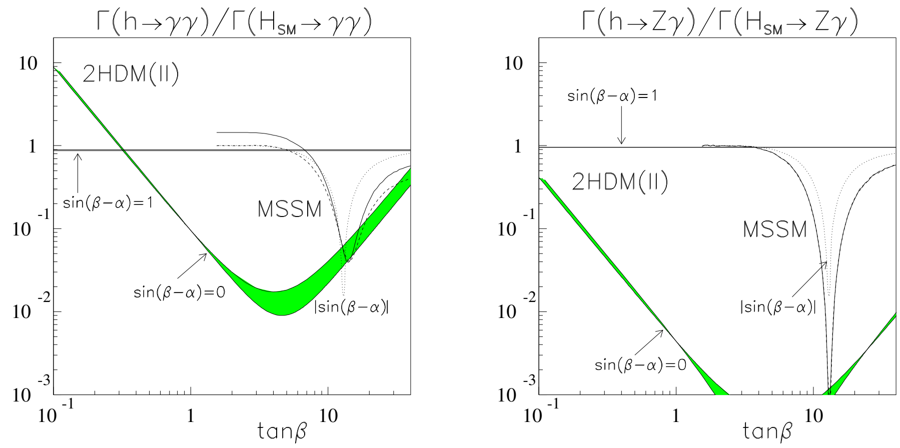

Figure 1: Ratios of the Higgs boson $h \to \gamma\gamma$ and $h \to Z\gamma$ decay widths in the 2HDM and the SM and between the MSSM and the SM as functions of $\tan\beta$. Results correspond to the Higgs mass M_h=100 GeV. In the 2HDM, the band for $\sin(\beta-\alpha)=0$ corresponds to the mass of the charged Higgs boson ranging from 165 GeV to infinity. For the MSSM curves, the solid ones include effects of supersymmetric loop particles (default masses), whereas the dashed ones do not. The dotted curve describes the function $|\sin(\beta-\alpha)|$ as a function of $\tan\beta$ for fixed mass M_h=100 GeV in the MSSM.

4 Results

We shall here present results for the $h \to \gamma\gamma$ and $h \to Z\gamma$ widths for a fixed Higgs boson mass equal to $M_h = 100$ GeV. The most recent values were taken for the fermion and gauge boson masses, and other parameters.[8]

In Fig. 1, we show the decay-rate ratios $\Gamma(h \to \gamma\gamma)/\Gamma(H^{\rm SM} \to \gamma\gamma)$ and $\Gamma(h \to Z\gamma)/\Gamma(H^{\rm SM} \to Z\gamma)$, for the 2HDM and the MSSM. For the 2HDM, we take $\sin(\beta-\alpha)=0$ and 1, and consider a range of values of the charged Higgs boson mass from 165 GeV to infinity. Let us first discuss the case of $\sin(\beta-\alpha)=0$. It is important to note that in this case, the lightest Higgs particle decouples from the W loops (see Eq. (1)). Thus, the decay rates are dominantly due to b and t quark loops (plus a small contribution from the charged Higgs particle). Dips appear for $\tan\beta \simeq 4$–5, where the b-quark starts to dominate over the t-quark contribution. The horizontal lines correspond to the 2HDM results for the case $\sin(\beta-\alpha)=1$ (see the numbers above).

For the MSSM, we have used the results of the program `HDECAY`.[9] The solid (dashed) curves correspond to supersymmetric particles contributing (or not) to the loops. Interestingly, for the $h \to Z\gamma$ decay, these two options are indistinguishable. The sharp dips in these ratios at $\tan\beta \sim 12$–14 correspond to the vanishing of $|\sin(\beta-\alpha)|$ (shown separately as a dotted curve), which determines the hWW coupling. In contrast to the 2HDM, this coupling is *not* a free parameter in the MSSM, since the Higgs mass here is kept fixed.

As mentioned above, for the MSSM, low values of $\tan\beta$ are not physical. Where the curves terminate at low $\tan\beta$, the charged Higgs mass is of the order of 10^5 GeV. The results discussed above were obtained for $M_h = 100$ GeV. We have checked that a similar picture holds for $M_h = 120$ GeV.

In summary, we have shown that the Higgs couplings involving one or two photons, which can be explored in detail at Photon Colliders ($\gamma\gamma$ and $e\gamma$), could resolve the models SM, 2HDM or MSSM with similar neutral Higgs boson masses in the range $M_h \sim 100$–120 GeV and having similar couplings to matter. In the case of different coupling to matter, a clear distinction can be made between the 2HDM and the MSSM.

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