Constraints on the Higgs sector from processes involving photons

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Abstract
The Higgs sector of the Standard Model and of the Two Higgs Doublet Extensions of SM, MSSM and the general 2HDM, can be tested in processes involving photons. A short review of the corresponding results is presented.

1 Introduction
The Higgs boson is still a missing element of the Standard Model (SM). The direct searches performed at LEP lead to the 95% C.L. lower limit $M_{Higgs} \geq 89.8$ GeV. The indirect analyses of the all electroweak data, where the quantum effects due to the other fundamental particles are taken into account, prefer the light SM Higgs boson (with mass below 262 GeV at 95 % C.L., [2]). The requirements of vacuum stability and the validity of perturbative theory up to the unification scale give the mass of the SM Higgs boson to be approximately between 130 and 180 GeV [2, 3].

In the Two Higgs Doublet Extensions of the SM, like Minimal Supersymmetric Standard Model (MSSM), more Higgs bosons are expected to exist: neutral scalars $h$ and $H$ (with mass $M_H \geq M_h$), a pseudoscalar (more properly a CP-odd particle) $A$ and charged scalars $H^\pm$ [4]. Such models are in addition to masses characterized by two parameters (assuming the CP conservation): a ratio of vacuum expectation values for two scalar fields $\tan \beta = v_2/v_1$ and $\alpha$, describing the mixing between two neutral scalar Higgs particles $h$ and $H$. These parameters govern the corresponding couplings of Higgs bosons to themselves (here the extra parameter, $\lambda_5$, appears) and to gauge bosons and fermions. Some of the Higgs couplings can be enhanced, some of them suppressed depending on values of parameters. In the so called Model II, one of Higgs doublets couples only to “up” components of the isodoublets, the other to the “down” components - this way the...
FCNC are naturally avoided (at the tree level). Then for large tan $\beta$ couplings of $h$ and $A$ to “down-type” quarks and charged leptons are highly enhanced while those to “up-type” quarks suppressed. Couplings to gauge bosons of the $h$ and $H$ are proportional to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$, respectively. The $A$ boson does not couple to $Z/W$ bosons.

In the MSSM there appear relations between parameters of the model: $\alpha$, $\beta$ and Higgs masses, leaving only two of them as independent parameters at the tree level. Therefore tide constraints on the Higgs boson masses are expected (with a surprisingly weak dependence on the sector of supersymmetric particles).

The non-supersymmetric version of the Model II, denoted here as 2HDM, has a Higgs sector the same as MSSM but the relations between parameters imposed by the supersymmetry are missing. Therefore each parameter has to be constrained independently. Vacuum stability analysis suggests that this model can not be valid up to the unification scale $\overline{\text{E}}$. This is exactly what is expected since the considered model can be treated as a low energy realization of the more fundamental theory.

We will see below (Sec.2) how much phenomenological consequences differ in these two approaches. The most striking difference is that much lighter Higgs bosons are allowed by the same data in 2HDM than in MSSM case.

The processes involving photons can test the Higgs sector of the SM and of its extensions. In my talk I will focus on the search for light neutral Higgs bosons in the framework of 2HDM at present (Sec. 3.1) and future experiments (Secs.3.2, 4 and 5).

## 2 Present limits on a non-minimal Higgs bosons

Not only in SM but also in MSSM neutral Higgs boson $h$ is expected to be light, with mass below 135 GeV ([4, 4]). On the other hand the present lower 95% C.L. limits from direct searches at LEP (for the CM energies up to 183 GeV) are as follows

$$M_h \geq 77 \text{ GeV \ and \ } M_A \geq 78 \text{ GeV}$$

for $\tan \beta \leq 0.8$ or $\tan \beta \geq 2.1$.

In Fig. 1a,b the OPAL results for the pseudoscalar and scalar based on LEP data (with the CM energy 183 GeV) are shown for $\tan \beta$ as a function of $M_A$ and $M_h$. For the allowed $(M_h, M_A)$ region, see Fig.2a.

In 2HDM even a lighter neutral Higgs particle is allowed by the present data, provided the other Higgs particles are heavy enough, $M_h + M_A \geq 50 \text{ GeV}$, see Fig.2b. Two scenarios are worth to be studied here:

$\rightarrow$ with a (very) light scalar $h$

$\rightarrow$ with a (very) light pseudoscalar $A$.

The strength of the pseudoscalar coupling to fermions, $\tan \beta$, in context of 2HDM was studied at LEP I by ALEPH group in the Yukawa process $e^+e^- \rightarrow Z \rightarrow \bar{f}fA$ [9]. These results are plotted in Fig. 3 (denoted “Yukawa”) to be compared to analogous results presented in Fig. 1a in context of MSSM.
Figure 1: a) The OPAL limits based on the LEP data at the CM energy 183 GeV for a) $\tan \beta$ versus mass $M_A$, b) $\tan \beta$ versus mass $M_h$ [7].

Figure 2: a) The limits for Higgs boson masses $M_A$ versus $M_h$ from OPAL analysis obtained in a) MSSM [7], b) 2HDM [8].
The present limits for $\tan \beta$ versus mass $M_h$ (solid lines) or $M_A$ (dashed lines) from analysis of the $Z \to h(A) + \gamma$ process at LEP I, compared to constraints from the $g$-2 for muon data [10] and the Yukawa process $e^+e^- \to f\bar{f}A$ at LEP I [9]. The regions above the upper and below the lower curves are excluded. For the scalar production experimental limits on $\sin(\beta - \alpha)$ from L3 [11] are included and two masses of the charged Higgs boson are assumed: 1) 54.5 GeV and 2) 300 GeV. From [12].

Figure 3: The present limits for $\tan \beta$ versus mass $M_h$ (solid lines) or $M_A$ (dashed lines) from analysis of the $Z \to h(A) + \gamma$ process at LEP I, compared to constraints from the $g$-2 for muon data [10] and the Yukawa process $e^+e^- \to f\bar{f}A$ at LEP I [9]. The regions above the upper and below the lower curves are excluded. For the scalar production experimental limits on $\sin(\beta - \alpha)$ from L3 [11] are included and two masses of the charged Higgs boson are assumed: 1) 54.5 GeV and 2) 300 GeV. From [12].

For charged Higgs boson mass there are constraints from the direct search performed at LEP, at the CM energy up to 183 GeV. The 95% C.L. limit is

$$M_{H^\pm} \geq 56 - 59 \text{ GeV}$$

for four LEP experiments [1]. This limit should hold both for MSSM and 2HDM, since the $ZH^+H^-$ coupling responsible for a charged Higgs bosons production at LEP does not depend on specific parameters of the Model II.

The undirect limit on the mass of a charged Higgs boson arises from the process $b \to s\gamma$. This process is mediated by loops and therefore it is a probe of the Standard Model and of its possible extensions. In context of 2HDM one gets $M_{H^\pm}$ to be above 165 GeV [13] for $\tan \beta$ larger than 2. (The analysis in the MSSM is more involved and will not be discussed here.)

The additional constraints on the Higgs bosons in the 2HDM arise from the data on the $g - 2$ for muon [10, 14], see Fig. 3.

3 The process $Z \to h(A) + \gamma$

3.1 LEP I

With the above limits in mind we can discuss now results from the analysis of the $Z \to h(A) + \gamma$ process, measurements of which were performed recently at the $Z$-resonance by
all four LEP experiments. The measured branching ratio is of order $10^{-6}$ to $10^{-5}$ \cite{15,12}. In the SM the scalar production is due to the $W$ and the fermions loop contributions (with a strong domination of the $W$-loop). The data are well above the SM prediction.

In the 2HDM the $Z \rightarrow h + \gamma$ proceeds via mentioned loops with $W$ and fermions, now with different couplings depending on the parameters $\alpha$ and $\beta$, and in addition via a charged Higgs boson loop. For the pseudoscalar production only fermions contribute. The results are given Fig.3 in form of the 95 \% C.L. exclusion plot for $\tan \beta$ versus mass of the $h$ or $A$. The comparison is made with the results based on the Yukawa process $e^+e^- \rightarrow f \bar{f}A$, and the muon anomalous magnetic moment data.

### 3.2 The “Z-factory” at Linear Colliders

This process can be studied with higher precision at the planned high luminosity “Z-factory” at Linear Colliders \cite{16,17,18}. In Fig. 4 the prediction based on the $Z \rightarrow A + \gamma$, assuming the integrated luminosity 20 fb$^{-1}$, is shown \cite{18}. The $Zh\gamma$ and $ZA\gamma$ couplings can be tested also in $e\gamma$ option of LC, see Sec.5.

### 4 Structure of photon and a search for a non-minimal Higgs bosons at HERA

The interesting opportunity to look for light neutral Higgs bosons in the framework of 2HDM is due to the photoproduction processes at $ep$ HERA collider \cite{19} (see also \cite{20}, where the SM Higgs boson production in processes involving the partonic content of the

![Exclusion plot (95 \% C.L.)](image_url)
photon was studied). Here the Higgs boson production with mass below 40-50 GeV is dominated by subprocesses due to the partonic content of the photon. In particular the process

\[ g\gamma g \rightarrow h(A), \]

with subsequent decay into \( \tau \) pairs was studied in detail. We found that for this channel and for the tagged electron one can, at least in principle, get rid of a serious background due to \( \gamma g \rightarrow \tau^+ \tau^- \). On the other hand the \( b\bar{b} \) final state looks very difficult.

The expected exclusion for the \( \tan \beta \) versus Higgs boson mass based on the \( \tau \) channel is presented in Fig. 4. The potential of the HERA collider to search for a light Higgs boson is larger than it follows from this plot, as in addition there are other contributions due to subprocesses, with and without the partonic content of the photon (like \( \gamma b\bar{b}, b\gamma b\bar{b} \) etc.).

Note that the light Higgs bosons from 2HDM can be also produced in \( \gamma\gamma \) fusion in eA collision at HERA.

5 \( \gamma e \) and \( \gamma\gamma \) Linear Colliders

The Linear Colliders running as \( \gamma e \) and \( \gamma\gamma \) Linear Colliders, with high energy photon beams obtained in the back Compton scattering on a laser light, offer excellent probe of the \( Zh\gamma, ZA\gamma \) and \( \gamma\gamma h \) or \( \gamma\gamma A \) couplings. All these couplings are of great importance for testing the structure of the Standard Model and of the MSSM or 2HDM.

The very low energy \( \gamma\gamma \) collider has been suggested some time ago as a test machine for the NLC. The potential of such collider in searching for a light neutral Higgs boson in 2HDM was studied in [31]. The results, based on the \( h(A) \) decays into muons, are plotted in Fig. 4. The work for a light neutral Higgs bosons production in 2HDM at the higher energy photon colliders is in progress.

6 Summary and outlook

The processes involving photons play an important role in constraining the Higgs sector of the Standard Model and of its extensions. The potential of the future Linear Colliders, including Photon Colliders, in testing the basic structure of the theory is large.

These colliders have also an unique potential in getting insight in the structure of photon at much higher energy than present experiments. The option \( e\gamma \) has an additional advantage - it allows to test the structure of really \( \text{real} \) photon. The reconstruction of true kinematical variables, a source of large errors in the present (and presumably future) experiments measuring the structure of photon in \( e^+e^- \) colliders (see eg. [32]), should be straightforward here. The perfect knowledge of the structure of photon is needed not only to test the strong interaction sector of the Standard Model but also to control the background for the New Physics.

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