Testing Higgs Physics at the Photon Collider

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Abstract

Here we review potential of the Photon Collider for study of Higgs physics after discovery of the SM-like Higgs boson at the LHC. In general, the Photon Collider will fill in the LHC and ILC results, giving in some cases unique information which cannot be obtained at other machines.

A Photon Collider (hereafter we use abbreviation PLC – Photon Linear Collider) is based on photons obtained from laser light back-scattered from high-energy electrons of Linear Collider (LC). Various high energy gamma-gamma and electron-gamma processes can be studied here. With a proper choice of electron beam and laser polarization, the high-energy photons with high degree polarization (dependent on energy) can be obtained. The direction of this polarization can be easily changed by changing the direction of electron and laser polarization. By converting both electron beams to the photon beams one can study $\gamma\gamma$ interactions in the energy range up to $\sqrt{s_{\gamma\gamma}} \sim 0.8 \cdot \sqrt{s_{ee}}$, whereas by converting one beam only the $e\gamma$ processes can be studied up to $\sqrt{s_{e\gamma}} \sim 0.9 \cdot \sqrt{s_{ee}}$ [1].

In a nominal LC option, i.e. with the electron-beam energy of 250 GeV, the geometric luminosity $L_{geom} = 12 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ can be obtained, which is about four times higher than the expected $e^+e^-$ luminosity. Still, the luminosity in the high energy $\gamma\gamma$ peak (see Fig. 1) corresponds to about $\frac{1}{3}$ of the nominal $e^+e^-$ luminosity – so we expect $L_{\gamma\gamma}(\sqrt{s_{\gamma\gamma}} > 0.65 \cdot \sqrt{s_{ee}})$ equal to about $100 \text{fb}^{-1}$ per year (400 $\text{fb}^{-1}$ for a whole energy range) [2,3]. Adjusting the initial electron beam energy and direction of polarizations of electrons and laser photons at fixed laser photon energy one can vary a shape of the $\gamma\gamma$ effective mass spectrum.

At a $\gamma\gamma$ collider the neutral C-even resonance with spin 0 can be produced, in contrast to C-odd spin 1 resonances in the $e^+e^-$ collision. Simple change of signs of polarizations of incident electron and laser photon for one beam transforms PLC to a mode with total helicity 2 at its high-energy part. It
allows to determine degree of possible admixture of state with spin 2 in the observed Higgs state. The s-channel resonance production of \( J^{PC} = 0^{++} \) particle allows to perform precise measurement of its properties at PLC.

- In summer 2012 a Higgs boson with mass about 125 GeV has been discovered at LHC [4]. We will denote this particle as \( H \). The collected data [5, 6] allow to conclude that the SM-like scenario, suggested e.g. in [7, 8], is realized [9]: all measured \( H \) couplings are close to their SM-values in their absolute value. Still following interpretations of these data are discussed: A) \( H \) is Higgs boson of the SM. B) We deals with phenomenon beyond SM, with \( H \) being some other scalar particle (e.g. one of neutral Higgs bosons of Two Higgs Doublet Model (2HDM) – in particular MSSM, in the CP conserving 2HDM that are \( h \) or \( H \)). In this approach following opportunities are possible: 1) Measured couplings are close to SM-values, however some of them (especially the \( \text{ttH} \) coupling) with a ”wrong” sign 2) In addition some new heavy charged particles, like \( H^\pm \) from 2HDM, can contribute to the loop couplings. 3) The observed signal is not due to one particle but it is an effect of two or more particles, which were not resolved experimentally – the degenerated Higgses. Each of these opportunities can lead to the enhanced or suppressed, as compared to the SM predictions, \( \mathcal{H}_\gamma \gamma, Hgg \) and \( HZ\gamma \) loop-coupling.

- The case with the observed Higgs-like signal being due to degenerated Higgses \( h_i \) demands a special effort to diagnose it. In this case the numbers of events with production of some particle \( x \) are proportional to sums like \( \sum_j (\Gamma_j^i / \Gamma_i^{\text{tot}}) \Gamma_{gg}^j \). Data say nothing about couplings of the individual Higgs particles and there are no experimental reasons in favor of the SM-like scenario for one of these scalars. In such case each of degenerated particles have low total width, and there is a hope that the forthcoming measurements at PLC can help to distinguish different states due to much better effective mass resolution. The comparison of different production mechanisms at LHC, \( e^+ e^- \) LC and PLC will give essential impact in the problem of resolution of these degenerated states. Below we do not discuss the case with degenerated Higgses with masses \( \sim \)125 GeV in more details, concentrating on the case when observed is one Higgs boson \( \mathcal{H} \), for which the SM-like scenario is realized.

- In the discussion we introduce useful relative couplings, defined as ratios of the couplings of each neutral Higgs boson \( h_i^{(i)} \) from the considered model, to the gauge bosons \( W \) or \( Z \) and to the quarks or leptons \( (j = V(W, Z), u, d, \ell...) \), to the corresponding SM couplings: \( \chi_j^{(i)} = g_j^{(i)} / g_j^{\text{SM}} \). Note that all couplings to EW gauge bosons \( \chi_V^{(i)} \) are real, while the couplings to fermions are generally complex. For CP-conserving case of 2HDM we have in particular \( \chi_h^h, \chi_h^d, \chi_h^\ell \) (with \( \chi_h^f = 0 \)), where couplings of fermions to \( h \) and \( H \) are real while couplings to \( A \) are purely imaginary.

The SM-like scenario for the observed Higgs \( \mathcal{H} \), to be identified with some neutral \( h_i^{(i)} \), corresponds to \( |\chi_j^{(i)}|^2 \approx 1 \). Below we assume this scenario is realized at present.

- It is known already from a long time that the PLC is very good observatory of the scalar sector of the SM and beyond SM, leading to important and in many cases complementary to the \( e^+ e^- \) LC case tests of the EW symmetry breaking mechanism [10-19]. The \( e^+ e^- \) LC, together with its PLC options (\( \gamma\gamma \) and \( e\gamma \)), is very well suited for the precise study of properties of this newly discovered \( \mathcal{H} \) particle, and other scalars. In particular, the PLC offers a unique opportunity to study resonant production of Higgs bosons in the process \( \gamma\gamma \to \text{Higgs} \) which is sensitive to charged fundamental particles of the theory. In principle, PLC allows to study also resonant production of heavier neutral Higgs particles from the extension of the SM. Other physics topic which could be studied well at PLC is the CP property of Higgs bosons. Below we discuss the most important aspects of the Higgs physics which can be investigated at PLC. Our discussion is based on analyses done during last two decades and takes into account also some recent ”realistic” simulations supporting those results.
I. Studies of 125 GeV Higgs $\mathcal{H}$

The discussion in this section is related to the case when $\mathcal{H}$ is one of the Higgs bosons $h^{(i)}$ of 2HDM. In the CP conserving case of 2HDM it can be either $h$ or $H$.

- Several NLO analyses of the production at the PLC of a light SM-Higgs boson $H_{SM}$ decaying into $b\bar{b}$ final state were performed, including the detector simulation, eg. [20]–[23]. These analyses demonstrate a high potential of this collider to measure accurately the Higgs two-photon width. By combining the production rate for $\gamma\gamma \rightarrow H_{SM} \rightarrow b\bar{b}$ (Fig. 2), to be measured with 2.1 % accuracy, with the measurement of the $Br(H_{SM} \rightarrow b\bar{b})$ at $e^+e^-$ LC, with accuracy $\sim 1 \%$, the width $\Gamma(H_{SM} \rightarrow \gamma\gamma)$ for $H_{SM}$ mass of 120 GeV can be determined with precision $\sim 2 \%$. This can be compared to the present value of the measured at LHC signal strength for 125 GeV $\mathcal{H}$ particle, which ratio to the expected signal for SM Higgs with the same mass (approximately equal to the ratio of $|g_{\gamma\gamma H}|^2/|g_{\gamma\gamma H_{SM}}|^2$), are 1.55+0.33−0.28 and 0.78 ±0.28/0.26 from ATLAS [5] and CMS [6], respectively.

- The process $\gamma\gamma \rightarrow \mathcal{H} \rightarrow \gamma\gamma$ is also observable at the PLC with reasonable rate [23]. This measurement allows to measure directly two-photon width of Higgs without assumptions about unobserved channels, couplings, etc.

- Neutral Higgs resonance couples to photons via loops with charged particles. In the Higgs $\gamma\gamma$ coupling the heavy charged particles, with masses generated by the Brout-Englert-Higgs-Kibble mechanism, do not decouple. Therefore the $\mathcal{H} \rightarrow \gamma\gamma$ partial width is sensitive to the contributions of charged particles with masses even far beyond the energy of the $\gamma\gamma$ collision. This allows to recognize which type of extension of the minimal SM is realized. The $H^+$ contribution to the $H\gamma\gamma$ loop coupling is proportional to $H H^+ H^−$ coupling, which value and sign can be treated as free parameters of model[The simplest example gives a 2HDM with Model II Yukawa interaction (2HDM II). For a small $m_{12}^2$ parameter the contribution of the charged Higgs boson $H^+$ with mass larger than 400 GeV leads to 10% suppression in the $H \rightarrow \gamma\gamma$ decay width as compare to the SM one, for $M_H \approx 120$ GeV [8] [7]. Table [1] (solution A). The enhancement or decreasing of the $H\gamma\gamma$ coupling is possible, as discussed for 2HDM with various Yukawa interaction models in [24]–[31] as well as in the Inert Doublet Model[32] [33] [34].

In the Littlest Higgs model a 10% suppression of the $\gamma\gamma$ decay width for $M_H \approx 120$ GeV is expected due to the new heavy particles with mass around 1 TeV at the suitable scale of couplings for these new particles [31], [35]. Fig. [8]

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1. Except if some additional symmetry is present in the model.
2. That is the $Z_2$ symmetric 2HDM where one Higgs doublet plays a role of SM Higgs field $\phi$, interacting with fermions as in Model I, with the SM-like Higgs boson $h$ and another Higgs doublet $\phi_D$, having no v.e.v.. The latter one contains four scalars $D, D^A, D^\pm$, the lightest among them $D$ (analog of $H$ of 2HDM) can be DM particle, scalars $D^A$ and $D^\pm$ (analog of $A$ and $H^\pm$, respectively).
The Higgs $\gamma\gamma$ loop coupling is sensitive to the relative signs of various contributions. For example, in 2HDM II sign of some Yukawa couplings may differ from the SM case, still strength (ie. absolute value) of all squared direct Higgs couplings to WW/ZZ and fermions being as in the SM. This may lead to the enhancement of the $\mathcal{H} \to \gamma\gamma$ decay-width with respect to the SM predictions, up to 2.28 for a "wrong" sign of the $\mathcal{H}tt$ for $M_H = 120$ GeV (1.28 for $\mathcal{H} \to gg$ and 1.21 for $\mathcal{H} \to Z\gamma$, respectively) coupling, Table 1 (solution $B_{Ht}$). The "wrong" sign of $\mathcal{H}bb$ coupling (solution $B_{Hb}$ in Table 1) could lead to a enhancement in the $\mathcal{H} \to gg$, and in the corresponding rate for gluon fusion of Higgs at LHC, similarly as the "wrong" sign of $\mathcal{H}tt$ coupling. Such solution is still considered as a possible for 125 GeV $\mathcal{H}$ particle [5].

Table 1: SM-like realizations in the 2HDM II [7],[8] together with ratios of loop-induced partial widths to their SM values at $M_H = 120$ GeV, $M_{H\pm} =800$ GeV, $|m_{12}^2| \leq 40$ GeV$^2$.

| solution | basic couplings | $|\chi_{gg}|^2$ | $|\chi_{\gamma\gamma}|^2$ | $|\chi_{Z\gamma}|^2$ |
|----------|----------------|---------------|------------------|----------------|
| $A_H$    | $\chi_V \approx \chi_b \approx \chi_t \approx \pm 1$ | 1.00 | 0.90 | 0.96 |
| $B_{Hb}$ | $\chi_V \approx -\chi_b \approx \chi_t \approx \pm 1$ | 1.28 | 0.87 | 0.96 |
| $B_{Ht}$ | $\chi_V \approx \chi_b \approx -\chi_t \approx \pm 1$ | 1.28 | 2.28 | 1.21 |

The observed Higgs particle can have definite CP parity or can be admixture of states with different CP parity (CP-mixing). In the latter case the PLC provides the best among all colliders place for the study of such mixing. Here, the opportunity to simply vary polarization of photon beam allows to study this mixing via dependence of the production cross section on the incident photon polarization [68],[38],[39],[41]. In particular, the change of sign of circular polarization ($++ \leftrightarrow --$) results in variation of production cross section of the 125 GeV Higgs in 2HDM by up to about 10%, depending on a degree of CP-admixture. Using mixed circular and linear polarizations of photons gives opportunity for more detailed investigations.

The important issue is to measure a Higgs selfcoupling, $\mathcal{H}\mathcal{H}\mathcal{H}$. In the SM this selfcoupling is precisely fixed via Higgs mass (and v.e.v. $v = 246$ GeV), while deviations from it’s SM value would be a clear signal of more complex Higgs sector. Both at the $e^+e^-$ collider and at the $\gamma\gamma$ collider the two neutral Higgs bosons are produced in processes both with and without selfinteraction, namely

$$e^+e^- \to Z \to \mathcal{H}(Z \to Z\mathcal{H}) \oplus e^+e^- \to Z \to Z(\mathcal{H} \to \mathcal{H}\mathcal{H});$$

$$\gamma\gamma \to \text{loop} \to \mathcal{H}\mathcal{H} \oplus \gamma\gamma \to \text{loop} \to \mathcal{H} \to \mathcal{H}\mathcal{H}.$$  

In the SM case the cross sections for above processes are rather low but measurable, so that coupling under interest can be extracted, both in the $e^+e^-$ and $\gamma\gamma$ modes of $e^+e^-$ LC, see [43]-[47]. The feasibility of this measurement at a PLC has been performed recently in [48]. For Higgs mass of 120 GeV and the integrating luminosity 1000 fb$^{-1}$ the statistical sensitivity as a function of the $\gamma\gamma$ energy for measuring the deviation from the SM Higgs selfcoupling $\lambda = \lambda_{SM}(1 + \delta \kappa)$ has been estimated. The optimum $\gamma\gamma$ collision energy was 3

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3 The recent analysis of the LHC data leads to constraints of the relative $\mathcal{H}tt$ coupling $\chi_t^2$ [56].
found to be around 270 GeV for a such Higgs mass, assuming that large backgrounds due
to \(WW/ZZ\) and \(bb\) production can be suppressed for correct assignment of tracks. As
a result, the Higgs pair production can be observed with a statistical significance of 5 \(\sigma\)
by operating the PLC for 5 years.

- The smaller but interesting effects are expected in \(e\gamma \to eH\) process with
\(p_{\perp e} > 30\) GeV, where \(HZ\gamma\) vertex can be extracted with reasonable accuracy [19].

II. Studies of heavier Higgses, for 125 GeV \(\mathcal{H} = h^{(1)}\)

A direct discovery of other Higgs bosons and measurement of their couplings to gauge
bosons and fermions is necessary for clarification the way the SSB is realized. In this
section we consider the case when observed 125 GeV Higgs is the lightest neutral Higgs,
\(\mathcal{H} = h^{(1)}\) (in particular in the CP-conserving case this means \(\mathcal{H} = h\)). A single Higgs
production at \(\gamma\gamma\) collider allows to explore roughly the same mass region for neutral
Higgs bosons at the parent \(e^+e^-\) LC but with higher cross section and lower background.
The \(e\gamma\) collider allows in principle to test wider mass region in the process \(e\gamma \to eH, eA\)
however with a lower cross section.

- Before general discussion, we present some properties of one of the simplest Higgs
model beyond the minimal SM, namely 2HDM (in particular, also the Higgs sector of
MSSM), having in mind that the modern data are in favour of a SM-like scenario. Let us
enumerate here some important properties of 2HDM for each neutral Higgs scalar \(h^{(i)}\) in
the CP conserving case \(h^{(1)} = h, h^{(2)} = H, h^{(3)} = A\):

A. For an arbitrary Yukawa interaction there are sum rules for coupling of different
neutral Higgses to gauge bosons \(V = W, Z\) and to each separate fermion \(f\) (quark or
lepton)

\[
\sum_{i=1}^{3} (\chi^{(i)}_{V})^2 = 1, \quad \sum_{i=1}^{3} (\chi^{(i)}_{f})^2 = 1.
\]  

(1)

The first sum rule (to the gauge bosons) was discussed e.g. in [50]–[53]. The second one
was obtained only for Models I and II of Yukawa interaction [54], however in
fact it holds for any Yukawa sector [56].

In the first sum rule all quantities \(\chi^{(i)}_{V}\) are real. Therefore, in SM-like case (i.e.
at \(|\chi^{(1)}_{V}| \approx 1\) both couplings \(|\chi^{(2)}_{V}|\) are small. The couplings entering the second
sum rule (for fermions) are generally complex. Therefore this sum rule shows that
for \(|\chi^{(1)}_{f}|\) close to 1, either \(|\chi^{(2)}_{f}|\) and \(|\chi^{(3)}_{f}|\) are simultaneously small, or
\(|\chi^{(2)}_{f}|^2 \approx |\chi^{(3)}_{f}|^2\).

B. For the 2HDM I there are simple relations, which in the CP conserved case are as
follows

\[
\chi^{(h)}_{u} = \chi^{(h)}_{d}, \quad \chi^{(H)}_{u} = \chi^{(H)}_{d}.
\]  

(2)

C. In the 2HDM II following relations hold:

a) The pattern relation among the relative couplings for each neutral Higgs particle
\(h^{(i)}\) [51] 52:

\[
(\chi^{(i)}_{u} + \chi^{(i)}_{d}) \chi^{(i)}_{V} = 1 + \chi^{(i)}_{u} \chi^{(i)}_{d}.
\]  

(3a)

b) For each neutral Higgs boson \(h^{(i)}\) one can write a horizontal sum rule [53]:

\[
|\chi^{(i)}_{u}|^2 \sin^2 \beta + |\chi^{(i)}_{d}|^2 \cos^2 \beta = 1.
\]  

(3b)
• Below, in Table 2, we present benchmark points for the SM-like h scenario in the CP conserving 2HDM II. The total widths for H and A for various $\chi_V^A = 1/\tan \beta$ are shown assuming with $\chi_V^h \approx 0.87, |\chi_V^{|h} = 0.5$ and $|\chi_V^{|A} = 1$ for H and A. 

| $M_{H,A}$ | $\Gamma_H$, $\Gamma_A$ | $\Gamma_H$, $\Gamma_A$ | $\Gamma_H$, $\Gamma_A$ |
|----------|---------------------|---------------------|---------------------|
| 200      | $0.35 \cdot 8 \cdot 10^{-5}$ | $0.35 \cdot 4 \cdot 10^{-3}$ | 0.4 | 0.2 |
| 300      | $2.1 \cdot 1.2 \cdot 10^{-4}$ | 2.1 | $6 \cdot 10^{-3}$ | 0.75 | 0.3 |
| 400      | 138 | 132 | 8.8 | 2.7 |
| 500      | 537 | 524 | 22.8 | 10.7 |

Table 2: Total width (in MeV) of H, A in some benchmark points for the SM-like h scenario ($M_h=125$ GeV) in the 2HDM ($\chi_V^h \approx 0.87, |\chi_V^{|h} = 0.5$ and $|\chi_V^{|A} = 1$). Results for $\tan \beta = 1/7, 1$ and 7 are shown.

In the SM-like h scenario it is follows from sum rule (1) that the W-contribution to the $H \gamma \gamma$ width is much smaller than that of would-be heavy SM Higgs, with the same mass, $M_{h_{SM}} \approx M_H$. At the large tan $\beta$ also $H \rightarrow t\bar{t}$, $A \rightarrow t\bar{t}$ decay widths are extremely small, so that the total widths of $H$, $A$ become very small.

• Let us compare properties of heavy $H$, $A$ in 2HDM with a would-be heavy SM Higgs-boson with the same mass. The cross section for production of such particles in the main gluon-gluon fusion channel, being $\propto \Gamma_H^g \Gamma_{H,A}^g / M_H^3$, is lower than that in SM. At large tan $\beta$ resonances $H, A$ become very narrow, as discussed above, besides, the two-gluon decay width become about $1/\tan^2 \beta$ smaller. So, in this main at LHC production channels cross section are roughly $1/\tan^4 \beta$ smaller than that for the would-be SM Higgs boson with the same mass and $H$ and $A$ can escape observation in these channels at LHC. (The same is valid for $e^+ e^-$ LC due to small value of $\chi_V^H$ for $H$ and $\chi_V^A = 0$.)

Moreover, in MSSM with $M_h = 125$ GeV we can have heavy and degenerate $H$ and $A$, $M_H \approx M_A$. At large tan $\beta$ discovery channel of $H/A$ at LHC is $gg \rightarrow b\bar{b} \rightarrow b\bar{b}H/A$. Nevertheless, in some region of parameters, at intermediate tan $\beta$, these $H$ and $A$ are elusive at LHC. That is so called LHC wedge region [57], see the latest analysis [58]. The PLC allows to diminish this region of elusiveness, since here the $H$ and $A$ production is generally not strongly suppressed and the $b\bar{b}$ background is under control [59, 60, 61]. The figs. [4] show that PLC allows to observe joined effect of $H$, $A$ within this wedge region. Precision between 11% to 21% for $M_A$ equal to 200-300 GeV, tan $\beta = 7$ of the Higgs-boson production measurement ($\mu = 200$ GeV and $A_f = 1500$ GeV) can be reached after one year [60]. To separate these resonances even in the limiting case $\chi_V^H = 0$ is a difficult task, since the total number of expected events is small.

• At $\chi_V^H \neq 0$, equal say 0.3-0.4 (what is allowed by current LHC measurement of couplings of $H = h$ to $ZZ$), an observation of $H \rightarrow ZZ$ decay channel can be good method for the $H$ discovery in 2HDM. The signal $\gamma \gamma \rightarrow H \rightarrow WW, ZZ$ interferes with background of $\gamma \gamma \rightarrow WW, ZZ$, what results in irregular structure in the effective-mass distribution of products of reaction $\gamma \gamma \rightarrow WW, ZZ$ (this interference is constructive and destructive below and above resonance, respectively). The study of this irregularity seems

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4 The total width $\Gamma_H$ differs from the total width $\Gamma_A$ by the W/Z contribution, since $\chi_V^A = 0$.

5 At $\tan \beta \ll 1$ we obtain the strong interaction in the Higgs sector mediated by $t$-quarks, what is signalizing by the fact that the calculated in standard approach total widths of heavy $H$, $A$ is becoming close to or even higher than the corresponding masses. Of course, in this case such tree-level estimates become inadequate. In the same manner at $\tan \beta > 70$ corresponds to the region of a strong interaction in the Higgs sector mediated by $b$-quarks. We don’t consider such scenarios.
Figure 4: Left: Production of $A$ and $H$, with parameters corresponding to the LHC wedge, at the $\gamma\gamma$ collider. Exclusion and discovery limits obtained for NLC collider for $\sqrt{s} = 630$ GeV, after 2 or 3 years of operation \cite{10}. Right: The case $M_H = M_A = 300$ GeV at $\chi_V^H \approx 0$ in the MSSM. Distributions of the corrected invariant mass $W_{\text{corr}}$ for selected $b\bar{b}$ events at $\tan\beta = 7$ \cite{60}.

...to be the best method for discovery of heavy Higgs, decaying to $WW$, $ZZ$ \cite{63}, and to measure the corresponding $\phi_{\gamma\gamma}$ phase, provided it couples to $ZZ/WW$ reasonably strong\textsuperscript{6}.

- Just as it was described above for the observed 125 GeV Higgs, PLC provides the best among colliders place for the study of spin and the CP properties of heavy $h^{(2)}$, $h^{(3)}$. That are CP parity in the CP conserved case (with $(h^{(2)}, h^{(3)} = (H, A)$), and (complex) degree of the admixtures of states with different CP parity, if CP is violated. This admixture determines dependence on the Higgs production cross section on direction of incident photon polarization \cite{38, 41, 70, 42}. These polarization measurements are useful in the study of the case when the heavy states $h^{(2)}$, $h^{(3)} (H, A)$ are degenerated in their masses. A study \cite{66} shows that the 3-years operation of PLC with linear polarization of photons, the production cross-section of the $H$ and $A$ corresponding to the LHC wedge for MSSM (with mass 300 GeV) can be separately measured with precision 20%. Pure scalar versus pure pseudoscalar states can be distinguished at 4.5 $\sigma$ level.

We point out on important difference between the $CP$ mixed and the mass-degenerate states. In the degeneracy of some resonances $A$ and $B$ one should distinguish two opportunities:

a) instrumental degeneracy when $|M_B - M_A| > \Gamma_B + \Gamma_A$, with mass difference within a mass resolution of detector. This effect can be resolved with improving of a resolution of the detector

b) physical degeneracy when $|M_B - M_A| < \Gamma_B + \Gamma_A$.

\textsuperscript{6} Similar calculations given in \cite{64} demonstrate this opportunity for a 2HDM version $B_{ha}$. 

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In the CP conserving case for both types of degeneracy the overlapping of $H$, $A$ resonances does not result in their mixing, and the production of a resonant state cannot vary with change of sign of photon beam polarization. In the CP violating case, the overlapping of resonances results in additional mixing of incident $h^{(2)}$, $h^{(3)}$ states, and the production cross-section varies with the change of polarization direction of incident photons.

- Another method for study of CP content of a produced particle provides the measurement of angular distribution of decay products. In the $t\bar{t}$ decay mode one can perform a study of the CP-violation, exploiting fermion polarization. The interference between the Higgs exchange and the continuum amplitudes can be sizable for the polarized photon beams, if helicities of the top and anti top quarks are measured. This enables to determine the CP property of the Higgs boson completely \cite{73, 74}, Fig. 5.

- The discovery of charged Higgses $H^{\pm}$ will be a crucial signal of the BSM form of Higgs sector. These particles can be produced both at the $e^+e^-$ LC ($e^+e^- \rightarrow H^+H^-$) and at the PLC ($\gamma\gamma \rightarrow H^+H^-$). These processes are described well by QED. The $H^+H^-$ production process at PLC has worse energy-threshold behaviour than the corresponding process at the $e^+e^-$ LC, but higher cross section. On the other hand, the process $e^+e^- \rightarrow H^+H^-$ can be analysed at LC better by measurements of decay products due to known kinematics. At the PLC the variation of a initial-beam polarization could be used for checking up spin of $H^\pm$ \cite{62}. See also analysis for Model III in \cite{78}.

- After a $H^{\pm}$ discovery, the observation of processes $e^+e^- \rightarrow H^+H^-h$ and $\gamma\gamma \rightarrow H^+H^-h$, $H^+H^-H$, $H^+H^-A$ may provide direct information on a triple Higgs ($H^+H^-h$) coupling $\lambda$, with cross sections in both cases $\propto \alpha^2\lambda^2$. The $\gamma\gamma$ collisions are preferable here due to a substantially higher cross section and opportunity of study polarization effects in the production process via variation of initial photon polarizations.

- Synergy of LHC, $e^+e^-$ LC and PLC colliders may be useful in determination of Higgs couplings, as different production processes dominating at these colliders lead to different sensitivity to gauge and Yukawa couplings. For example $e^+e^-$ LC Higgstrahlung...
leads to large sensitivity to the Higgs coupling to the EW gauge bosons, while at PLC $\gamma\gamma$ and $Z\gamma$ loop couplings depend both on the Higgs gauge and Yukawa couplings, as well as on coupling with $H^+$, see results both for CP conserving/CP violating in e.g. \cite{75, 76, 77}.

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