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SIMULATION OF THE HIGGS BOSON PRODUCTION AT LHC, ILC AND PHOTON LINEAR COLLIDER*

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Prospects for precise determination of the Higgs boson couplings from a combined analysis of LHC, ILC and the Photon Linear Collider data are studied in detail for the CP-conserving Two Higgs Doublet Model (II). LHC, ILC and the Photon Collider measurements are complementary, being sensitive to different coupling combinations. For the mass of the heavy scalar Higgs boson between 200 and 350 GeV, where ZZ and W^+W^- decay-channels dominate, only the combined analysis of the LHC, ILC and the Photon Collider data allows for unique determination of the basic Higgs boson couplings and for establishing evidence for the possible CP violation in 2HDM. Additional constraints on the model parameters can be obtained by combining available data for the production and decays of the heavy Higgs boson H with the corresponding measurements for the light Higgs boson h.

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1. Introduction

The physics potential of a Photon Linear Collider (PLC) is very rich and complementary to the physics program of the e^+e^- and hadron–hadron colliders. It is an ideal place to study the mechanism of the electroweak symmetry breaking (EWSB) and the properties of the Higgs boson. In this paper we continue our previous studies [1–3] and consider measurement of the basic Higgs boson couplings for the general Model II version of 2HDM.

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Only the combined analysis of LHC, Linear Collider and Photon Linear Collider data allow to establish a possible CP violation in the considered model.

2. Higgs boson couplings in the general 2HDM (II)

In the general 2HDM (II) [4] couplings of the neutral Higgs bosons to up- and down-type quarks (and leptons), and to vector bosons can be expressed in terms of two mixing angles, α and β, as shown in Table I.

TABLE I

Couplings of the neutral Higgs bosons to up- and down-type fermions, and to vector bosons, relative to the Standard Model couplings, for the general solution of 2HDM (II).

	h	H	A
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\,\gamma_5(1/\tan\beta)$
χ_d	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-i\,\gamma_5\,\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

These couplings, relative to the corresponding ones of the SM Higgs boson, are related by the so called "patter relations". Therefore, specifying two of the three couplings is sufficient for a description of the Higgs boson interactions at the tree level, assuming CP conservation. In the following we will consider production and decays of the heavy Higgs boson H. Instead of parameters of the model, angles α and β, we will use its basic relative couplings χ_V^H and χ_u^H, which can be treated as "observables", to parameterize cross sections and branching ratios. Moreover, couplings of the other neutral Higgs bosons h and A are also uniquely defined by χ_V^H and χ_u^H.

The general Two Higgs Doublet Model allows for CP violation through a mixing between H and A states. We consider a scenario with weak CP violation, where the couplings of the lightest mass-eigenstate h_1 correspond to the couplings of h boson, whereas relative couplings of mass-eigenstates h_2 and h_3 can be described as the superposition of H and A couplings:

$$\begin{aligned}\chi_X^{h_2} &\approx \chi_X^H \cos\Phi_{HA} + \chi_X^A \sin\Phi_{HA} \qquad (1)\\ \chi_X^{h_3} &\approx \chi_X^A \cos\Phi_{HA} - \chi_X^H \sin\Phi_{HA}\,,\end{aligned}$$

where X denotes a quark or a vector boson, $X = u, d, V$, and the mixing angle Φ_{HA} is assumed to be small. We study the feasibility of constraining the value of the mixing angle Φ_{HA} from the measurements of the heavy Higgs boson H (*i.e.* Higgs boson mass-eigenstate h_2 for $\Phi_{HA} = 0$) production.

3. Complementarity of LHC, ILC and PLC measurements

We consider determination of properties of the heavy scalar Higgs boson from the combined analysis of LHC, ILC and PLC data. For simplicity, we only consider H decays to W^+W^- or ZZ, as they are expected to dominate in the considered mass range between 200 and 350 GeV. Fig. 1 shows the Higgs boson production rates times W^+W^-/ZZ branching ratios, at LHC, ILC and PLC, as a function of basic relative couplings to the vector bosons, χ_V, and to the up-type quarks, χ_u. Cross section measurements at different machines are complementary, being sensitive to different combinations of Higgs couplings: Higgs-strahlung from the Z boson and W^+W^- fusion processes at ILC are sensitive to the χ_V only whereas for the gluon fusion process at LHC the dominant contribution comes from χ_u. At the Photon Linear Collider both couplings (as well as their relative phase) are important, as the dominant contribution to the two-photon width comes from W and top-quark loops.

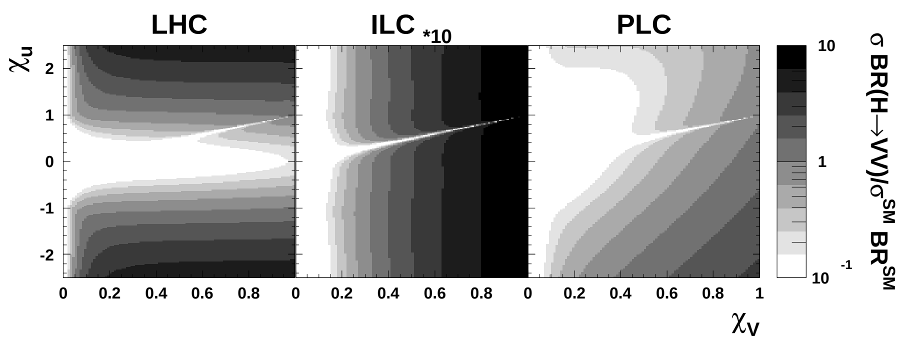

Fig. 1. The Higgs boson H production rates times the W^+W^-/ZZ branching ratios, relative to SM predictions, are presented as a function of basic relative couplings to the vector bosons (χ_V) and the up-type fermions (χ_u). Higgs boson production at LHC, ILC and PLC is studied for $M_H = 250$ GeV.

Complementarity of the LHC, ILC and PLC measurements of weak CP violation is shown in Fig. 2, where the expected h_2 production rates in W^+W^-/ZZ decay channel at LHC, ILC and PLC, are compared. The rates are presented as a function of the basic relative coupling to the up-type quarks, χ_u (LHC) or to the vector bosons, χ_V (ILC and PLC), and the CP-violating H–A mixing angle, Φ_{HA}. For small H–A mixing ($\Phi_{HA} \approx 0$) LHC and ILC measurements weakly depend on the mixing angle Φ_{HA}, since the cross section is dominated by one of the basic couplings, and there is no direct dependence on the coupling phase. At the Photon Linear Collider both couplings as well as their relative phase are important and the cross section is sensitive to the H–A mixing angle (and its sign) even for small Φ_{HA} values.

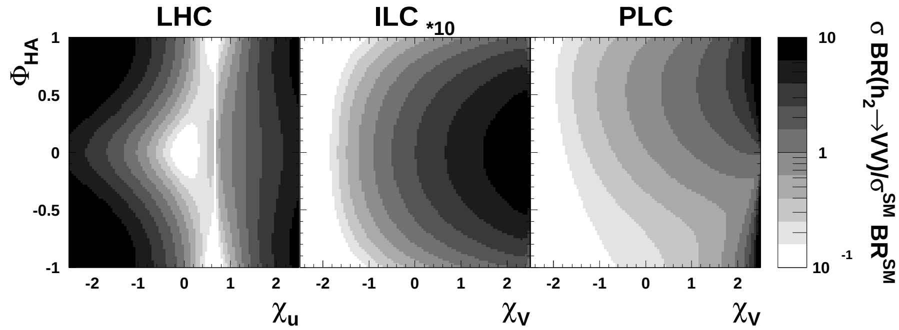

Fig. 2. The Higgs boson h_2 production rates times W^+W^-/ZZ branching ratios, relative to SM predictions, as a function of basic relative coupling to the vector bosons (χ_V) or the up-type fermions (χ_u), and the H–A mixing angle Φ_{HA}. Higgs boson production rates at LHC, ILC and PLC are shown for $M_{h_2} = 250$ GeV.

4. Analysis

For the Photon Linear Collider measurements we use the approach developed in [1, 2]. The invariant mass resolution obtained from a full simulation of $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to ZZ$ events, based on the PYTHIA and SIMDET programs and parametrized as a function of the $\gamma\gamma$ centre-of-mass energy, $W_{\gamma\gamma}$, is convoluted with the relevant cross-sections and with the CompAZ [5] parametrization of the luminosity spectra to obtain the expected signal distribution. Similar approach is used for the simulation of LHC and ILC measurements. We use the results of [6] for the expected invariant mass distribution of the Higgs boson signal ($pp \to H \to ZZ \to 4l$) and Standard Model background events at LHC. For the Higgs boson production via Higgs-strahlung and WW-fusion at ILC we use the results of [7]. In both cases the signal distribution is assumed to result from a simple convolution of the Breit–Wigner Higgs boson mass distribution with a detector resolution function. With this assumption we can scale the SM signal expectations presented in [6, 7] to any scenario of the 2HDM (II).

For each simulated set of LHC, ILC and PLC data, the Higgs boson couplings and CP-violating H–A mixing angle were used as the free parameters in the simultaneous fit of the expected distributions to all observed W^+W^- and ZZ mass spectra. One of the simulated sets of invariant-mass distributions (for a model with $\chi_V^H = 0.7$, $\chi_u^H = -1$, $\Phi_{HA} = 0$ and $M_H = 200$ GeV) is shown in Fig. 3, together with the fitted expectations of the model.

Additional parameters are added to the fit to take into account the systematic uncertainties. For the LHC we assume 10% systematic uncertainty in the normalization of the background and 20% total systematic uncertainty in the expected signal rate [8]. For ILC the uncertainties in both signal and

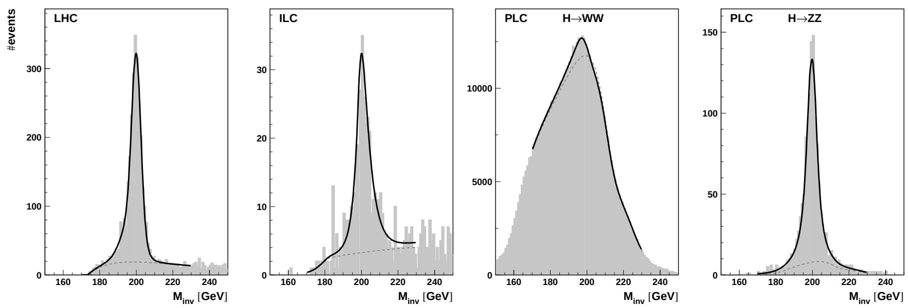

Fig. 3. Simulated invariant mass distributions for heavy Higgs boson at LHC (a), ILC (b) and PLC ((c) and (d), for W^+W^- and ZZ channels, respectively), for $\chi_V^H = 0.7$, $\chi_u^H = -1$, Φ_{HA}=0 and $M_H = 200$ GeV. Also shown is the result of the fit used for parameter determination.

background normalization are assumed to be 5%. For the PLC we take into account 5% uncertainty in the signal and 10% uncertainty in the background normalization, as well as 10% uncertainty in the parameters describing the shape of the luminosity spectra. The Higgs boson mass is also used as a free parameter in the combined fit, as there will be no other measurements to constrain its value.

5. Results

Values of the expected total errors on the basic Higgs boson couplings and on the H–A mixing angle Φ_{HA}, are shown in Fig. 4, for Higgs boson mass of 250 GeV and weak CP violation ($\Phi_{HA} \approx 0$). The errors on the couplings χ_V and χ_u, averaged over the considered parameter range, are 0.03 and 0.13, respectively. An average error on the H–A mixing angle Φ_{HA} is about 150 mrad, although it can be measured to better than 100 mrad in most of the considered parameter space.

The final step in verifying the coupling structure of the model is the comparison of direct H measurements with constraints on the model parameters resulting from other measurements in the Higgs sector. Fig. 5 compares constraints on the couplings χ_V^H and χ_u^H, used to parametrize the model (assuming no CP violation), obtained from measurements at LHC, ILC and PLC of the heavy Higgs boson (with mass of 250 GeV) and the light Higgs boson (with mass of 120 GeV). Measurements of the light Higgs boson production result in stringent constraints on the H couplings, which are comparable to the precision of the direct coupling determination from the combined fit to the H production data (indicated by the ellipse).

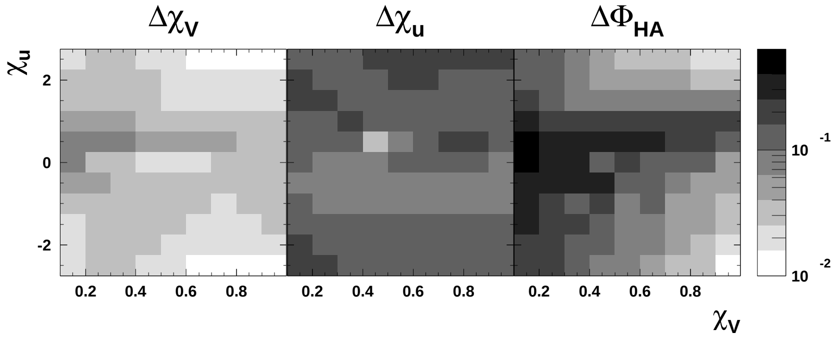

Fig. 4. The total errors on the basic Higgs boson couplings to vector bosons χ_V (left plot) and up-type fermions χ_u (middle plot), and on the H–A mixing angle Φ_{HA} (right plot), from combined fit to invariant mass distributions measured at LHC, ILC and PLC, for heavy Higgs boson mass $M_H = 250$ GeV and $\Phi_{HA} = 0$.

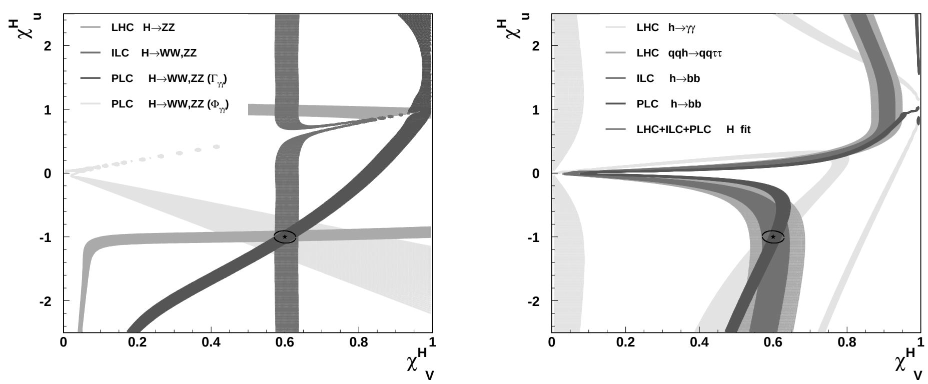

Fig. 5. Complementarity of LHC, ILC and PLC measurements in the determination of the 2HDM (II) parameters. The bands show values of the basic heavy Higgs boson couplings to vector bosons (χ_V^H) and up-type fermions (χ_u^H) consistent (on 1σ statistical error level) with heavy Higgs boson (left plot) and light Higgs boson (right plot) measurements at LHC, ILC and PLC. A model with $\chi_V^H = 0.6$, $\chi_u^H = -1$ (star) and H mass of 300 GeV is considered, while the mass of h is set to 120 GeV.

6. Summary

Prospects for precise determination of the Higgs boson couplings from a combined analysis of LHC, ILC and the Photon Linear Collider data are studied in detail for the Two Higgs Doublet Model (II), for mass of the heavy scalar Higgs boson between 200 and 350 GeV, where ZZ and W^+W^- decay-channels dominate. LHC, ILC and PLC measurements are complementary, being sensitive to different coupling combinations. For the model with CP violation, only the combined analysis of LHC, ILC and PLC measurements allows for the precise determination of the basic Higgs boson couplings χ_V and χ_u, and of the CP-violating H–A mixing angle Φ_{HA}. In most of the considered parameter space, the CP-violating mixing angle Φ_{HA} can be measured to better than 100 mrad. Additional constraints on the model parameters can be obtained by combining available data for the production and decays of the heavy Higgs boson H with the corresponding measurements for the light Higgs boson h.

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