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Determination of the basic Higgs-boson couplings from combined analysis of WW/ZZ decays at LHC, LC and Photon Collider.

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Abstract

The feasibility of measuring the Higgs-boson properties at the Photon Collider at TESLA has been studied in detail, using realistic luminosity spectra and detector simulation, for masses of Higgs bosons between 200 and 300 GeV. For the CP-conserving Two Higgs Doublet Model (II), the basic couplings to the vector bosons and up-type quarks can be determined at the Photon Collider from the combined measurement of the invariant-mass distributions in the ZZ and W^+W^- decay-channels. Cross section measurements at LHC, LC and Photon Collider are complementary being sensitive to different combinations of Higgs-boson couplings. We found that only combined analysis of data allows for unique determination of Higgs couplings and for establishing evidence for the CP-violation in 2HDM.

1 Introduction

A photon collider has been proposed as a natural extension of the e^+e^- linear collider [1]. The physics potential of a photon collider 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 paper [2] we performed realistic simulation of SM Higgs-boson production at the TESLA Photon Collider [3] for W^+W^- and ZZ decay channels, for Higgs-boson masses above 150 GeV. Due to the interference with a large Standard Model background, the process $\gamma\gamma \to higgs \to W^+W^-/ZZ$ turns out to be sensitive not only to the $\gamma\gamma$ partial width $\Gamma_{\gamma\gamma}$, but also to the phase of the $\gamma\gamma \to higgs$ coupling, $\phi_{\gamma\gamma}$. We found that precise measurements of both $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$ are crucial for determination of the Higgs-boson couplings, see also [4, 5, 6, 7, 8].

In paper [9] we extended this analysis to a particular version of the SM-like Two Higgs Doublet Model, the so called solution B_h, with and without CP-conservation. This version is characterized by only one parameter, $\tan\beta$, and it is especially suitable for feasibility studies. From the combined measurement of the invariant-mass distributions in the ZZ and W^+W^- decay-channels, the parameter of the model can be precisely determined. Taking into account possible systematic uncertainties of the measurement, we found out that after one year of the Photon Collider running the expected precision in the measurement of the Higgs-boson coupling ($\tan\beta$) is of the order of 10%, for both light and heavy scalar Higgs boson. In case of the Two Higgs Doublet Model (2HDM) solution B_h with a weak CP violation, the $H - A$ mixing angle can be constrained. For low $\tan\beta$ values precision of about 100 mrad can be obtained (in a small-mixing approximation).

In this paper we continue our feasibility study by considering measurement of the basic Higgs-boson couplings for the general Model II version of 2HDM. Also in this case, unique determination of the Higgs-boson couplings at the Photon Collider is possible. However, only combined analysis of LHC, Linear Collider and Photon Collider data allows to establish a possible CP-violation in the considered model.

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

In the general 2HDM (II) [10] 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 1. These couplings, relative to the corresponding ones of the SM Higgs boson, are related by the so called "patter relation". For each neutral Higgs boson[1]

$$(\chi_V - \chi_d)(\chi_u - \chi_V) + \chi_V^2 \;\; = \;\; 1\,.$$

[1]For model with CP violation similar relations hold for each neutral Higgs particle: h_1, h_2 and h_3

	h	H	A
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\ \gamma_5\ \frac{1}{\tan\beta}$
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

Table 1: 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).

Therefore, specifying two of the three couplings is sufficient for a description at the tree level of the Higgs-boson interactions, assuming CP conservation. For example, coupling to the down-type quarks (and charged leptons) can be expressed by couplings to the vector boson and up-type quarks:

$$\chi_d \;=\; \chi_V + \frac{1-\chi_V^2}{\chi_V - \chi_u}\,. \tag{1}$$

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 to parametrize cross sections and branching ratios basic relative couplings χ_V and χ_u, which can be treated as "observables". The advantage of this approach is that, neglecting small contribution to the total width coming from H decays to hh, results presented for H are also valid for h (assuming the same basic relative couplings and mass). As the overall sign of Higgs couplings does not change the numerical results on the tree level, we restrict our analysis to

$$0 \;\leq\; \chi_V \;\leq\; 1\,.$$

In the general Two Higgs Doublet Model the mass eigenstates of the neutral Higgs-bosons h_1, h_2 and h_3 do not match CP eigenstates h, H and A [11]. The model allows for an indirect CP violation through a small mixing between H and A states. We consider scenario with weak CP violation, where the couplings of the lightest mass-eigenstate h_1 (with mass 120 GeV) are expected to correspond to the couplings of h boson, whereas couplings of h_2 and h_3 states can be described as the superposition of H and A couplings. For relative basic couplings (see table 1) we have:

$$\begin{aligned}
\chi_X^{h_1} &\approx \chi_X^h \\
\chi_X^{h_2} &\approx \chi_X^H \cdot \cos\Phi_{HA} \;+\; \chi_X^A \cdot \sin\Phi_{HA} \\
\chi_X^{h_3} &\approx \chi_X^A \cdot \cos\Phi_{HA} \;-\; \chi_X^H \cdot \sin\Phi_{HA}
\end{aligned} \tag{2}$$

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 the determination of the mixing angle Φ_{HA} from the measurement of the Higgs-boson mass-eigenstate h_2.

3 Analysis

The Compton back-scattering of a laser light off high-energy electrons is considered as a source of high energy, highly polarized photon beams at Photon Collider [1]. Our analysis uses the CompAZ parametrization [12] of the realistic luminosity spectra for a Photon Collider at TESLA [13]. We assume that the centre-of-mass energy of colliding electron beams, $\sqrt{s_{ee}}$, is optimised for the production of a Higgs boson with a given mass. The event generation according to the cross-section formula for a vector-boson production (direct production in $\gamma\gamma$ interactions, Higgs-boson decays into the vector bosons and contribution from the interference terms) [4, 5, 14] is based on PYTHIA 6.152 [15]. The fast simulation program SIMDET version 3.01 [16] is used to model the TESLA detector performance. The selection cuts are applied to select $\gamma\gamma \to W^+W^- \to q\bar{q}q\bar{q}$ and $\gamma\gamma \to ZZ \to l\bar{l}q\bar{q}$ events ($l = \mu,\ e$). Details of event selection are given in [2]. All results presented in this paper were obtained for an integrated luminosity corresponding to one year of the photon collider running, as given by [13].

The invariant-mass resolution obtained from a full simulation of W^+W^- and ZZ events, based on the PYTHIA and SIMDET programs, has been parametrized as a function of the $\gamma\gamma$ centre-of-mass energy, $W_{\gamma\gamma}$. The parametric description of the expected invariant mass distributions for $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to ZZ$ events can be then obtained by the numerical convolution of the relevant cross-sections with the CompAZ spectra and the parametrized resolution. Based on this description, for each set of model parameter values considered many experiments were simulated, each corresponding to one year of a Photon Collider running at TESLA at a nominal luminosity.

Similar approach is used for the simulation of measurements at LHC and LC. We use results of [17] 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 Higgs-boson production via Higgs-strahlung and WW-fusion at LC we use results of [18]. 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 [17, 18] to any scenario of the 2HDM (II). Interference between signal and background processes is neglected.

For each simulated set of LHC, LC and PC data, Higgs-boson couplings (and CP-violating H-A mixing angle in case of CP-violation) were used as the free parameters in the simultaneous fit of the expected distributions to all observed W^+W^- and ZZ mass spectra. In this approach, the expected errors on the model parameters can be directly obtained from the fit.

To take into account systematic uncertainties additional parameters are added to the fit. For Photon Collider we take into account uncertainty in the total $\gamma\gamma$ luminosity and in the shape of the luminosity spectra, as described in [9]. For LHC we assume 10% systematic uncertainty in the normalization of the background and in the hadron-level cross section calculations for the signal [19]. For LC the uncertainty in the background normalization is assumed to be 5%. The Higgs-boson mass is also used as a free parameter in the combined fit, as there will be no

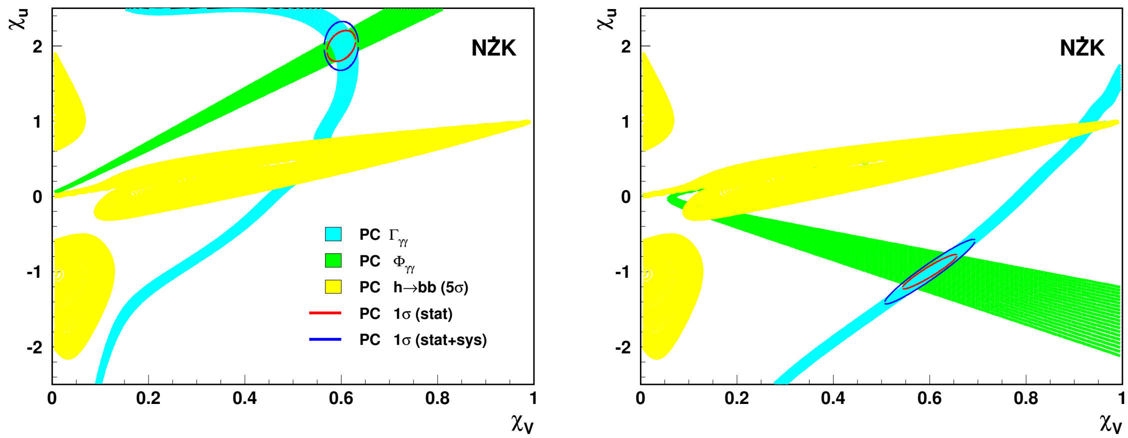

Figure 1: Determination of the basic Higgs-boson couplings to the vector boson (χ_V) and up-type quarks (χ_u) from a combined fit to W^+W^- and ZZ invariant mass distributions, for Higgs-boson mass of 300 GeV. Expected statistical (red) and total (blue) error contours (1σ) are shown for $\chi_V = 0.7$ and $\chi_u = 1.5$ (left plot) and for $\chi_V = 0.7$ and $\chi_u = -1$ (right plot). Parameter regions consistent with two-photon width $\Gamma_{\gamma\gamma}$ and phase $\phi_{\gamma\gamma}$ measurements (on 1σ statistical error level) are shown as cyan and green bands, respectively. Parameter region marked in yellow will be excluded if no decays into $b\bar{b}$ are observed.

other measurements to constrain its value.

4 Measurements at the Photon Collider

In case of the CP-conserving 2HDM (II), a combined analysis of the W^+W^- and ZZ invariant mass distributions is sufficient for the simultaneous determination of both Higgs-boson couplings χ_V and χ_u. Measurement of the two-photon width $\Gamma_{\gamma\gamma}$ and phase $\phi_{\gamma\gamma}$ uniquely determines both couplings. This is illustrated in Figure 1 for two chosen sets of parameter values. Bands corresponding to coupling values consistent (on 1σ statistical error level) with $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$ measurements show that in both cases an unique determination of both couplings is possible. Expected statistical error contours, from direct fits of χ_V and χ_u to the observed invariant mass distributions, are included for comparison. Consistent results are obtained with both approaches. Error contours resulting from the fit including systematic uncertainties are also shown. For both sets of chosen parameter values, systematic uncertainties affect mainly the phase $\phi_{\gamma\gamma}$ measurement.

Accuracy in determination of the Higgs-boson couplings was studied for the wide range of coupling values. Expected statistical and total error contours, obtained for the case of the heavy Higgs boson with mass of 250 GeV, are shown in Figure 2. The total errors, expected in the determination of χ_V and χ_u, are shown in Figure 3, for Higgs-boson mass of 250 GeV. For most of the considered coupling values, $0.2 \leq \chi_V \leq 0.9$ and $-2 \leq \chi_u \leq 2$, the error on χ_V is about or below 0.1, whereas for χ_u the error is about 0.4. In both cases smaller errors are expected for $\chi_u > 0$, i.e. when both couplings have the same sign. The dependence of the expected coupling errors on the assumed Higgs-boson mass was also studied. For the χ_V measurement the expected errors tend to increase slightly with mass. The average error, over the considered parameter range, changes from about 0.082 at 200 GeV to 0.090 at 300 GeV. For χ_u measurement systematic decrease of the expected error is observed, from average error of 0.49 at 200 GeV to 0.36 at 300 GeV.

5 Combined analysis of LHC, LC and Photon Collider data

Our results presented above show, that the Photon Collider by itself, should allow for an unique determination of the Higgs-boson couplings. However, it is clear that precise measurements of the Higgs-boson production will earlier be available at LHC and LC. Therefore we also consider measurement of the Higgs-boson properties from the combined analysis of LHC, LC and Photon Collider data. For simplicity, we only consider Higgs-boson decays to W^+W^- or ZZ, as in the considered mass range they are expected to dominate (except for the very special choice of model parameters, e.g. when coupling to down-type fermions is very large).

Figure 4 shows the expected Higgs-boson production rates times W^+W^-/ZZ branching ratios, at LHC, LC and PC, as a function of basic relative couplings to the vector bosons, χ_V, and to the up-type quarks, χ_u. The Higgs boson H is considered for mass equal to 250 GeV. Cross section measurement at different machines are complementary, as they are sensitive to different combinations of Higgs couplings: Higgs-strahlung from Z boson and W^+W^- fusion processes at LC 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 Collider both couplings (as well as their relative sign) are important, as the dominant contribution to the two-photon width comes from W and top-quark loops. Suppression of the Higgs-boson production rates, expected along $\chi_u = \chi_V$ line, is due to the fact that the coupling to the down-type quarks can be very large in this limit (see Eq. 1), and decays to $b\bar{b}$ start to dominate.

Complementarity of the LHC, LC and Photon Collider measurements in the determination of the model parameters is also shown in Figure 5. The color bands show values of the Higgs-boson couplings, calculated assuming CP-conserving 2HDM (II), consistent with the individual measurements. Results obtained for experimental data simulated without and with CP-violation are compared. In case of no CP violation, absolute values of both couplings can already be measured based on LHC and LC measurements. However, only by including the Photon Collider data determination of their relative sign is possible.

Consistent description of LHC, LC and PC data is only possible if both couplings as well

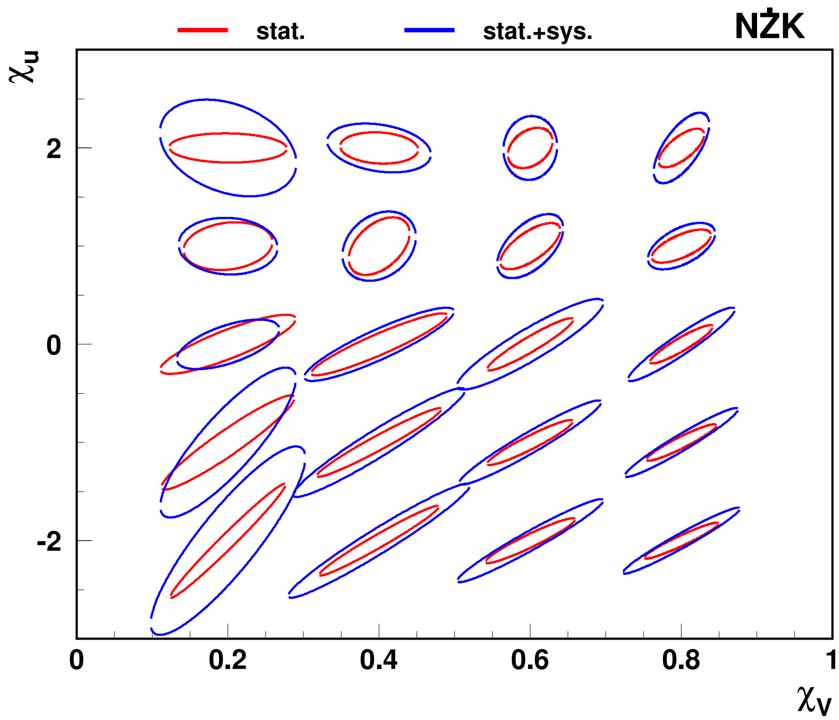

Figure 2: Expected statistical (red) and total (blue) error contours (1σ) in the determination of the basic Higgs-boson couplings to vector bosons (χ_V) and up fermions (χ_u) from combined fit to W^+W^- and ZZ invariant mass distributions, for heavy Higgs-boson mass of 250 GeV.

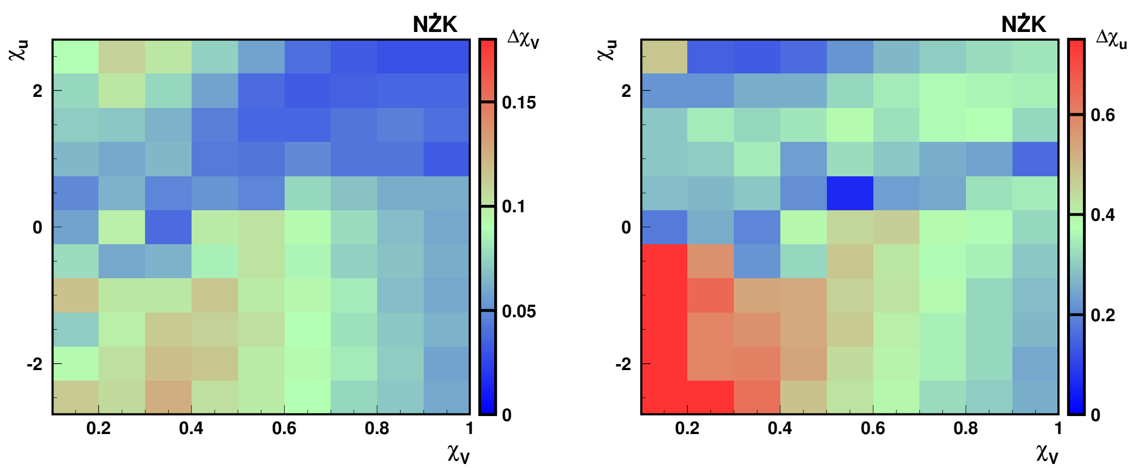

Figure 3: Expected total errors in the determination of the basic Higgs-boson coupling to vector bosons, χ_V (left plot) and to up fermions, χ_u (right plot), as a function of the assumed coupling values, for heavy Higgs-boson mass of 250 GeV.

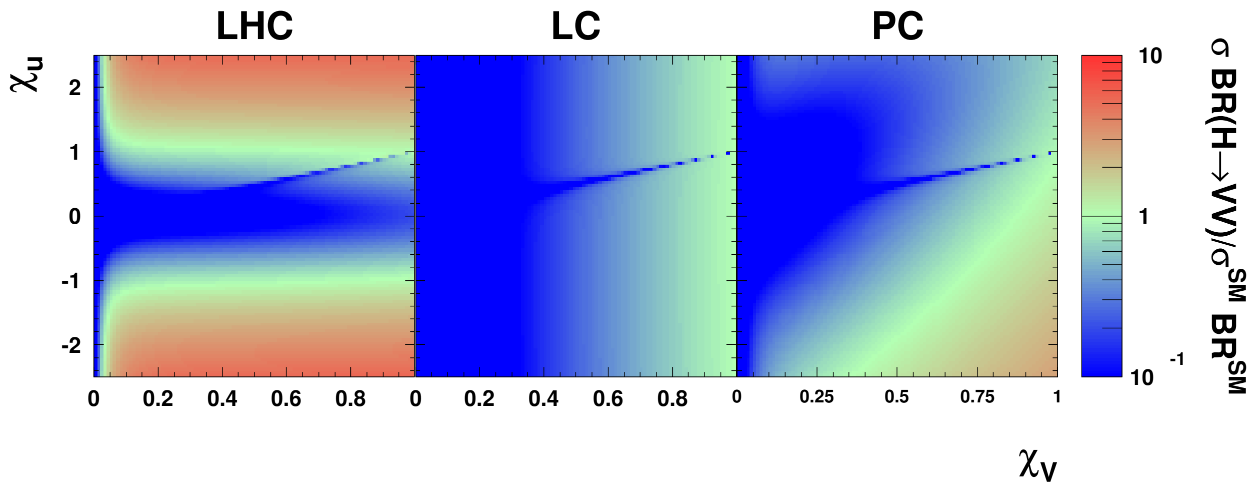

Figure 4: Expected Higgs-boson H production rates times W^+W^-/ZZ branching ratios, relative to SM predictions, as a function of basic relative couplings to vector bosons (χ_V) and up fermions (χ_u). Higgs-boson production at LHC, LC and Photon Collider is studied for $M_H = 250$ GeV.

as their relative phase are properly measured. If discrepancies between measurements are observed, when analysed within CP-conserving 2HDM (II) (see right plot in Figure 5), this could be an evidence for indirect CP-violation. In such a case only a combined analysis of LHC, LC and PC 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}. It should be stressed that, in the considered case of CP violation via $H-A$ mixing, only invariant mass distribution is sensitive to the mixing angle Φ_{HA}. Angular correlations in Higgs-boson decays $h_2 \rightarrow WW/ZZ \rightarrow 4f$, which can be used to establish an evidence for direct CP-violation in Higgs-boson couplings [8, 17, 20] are not sensitive to indirect CP violation via mixing of pure scalar and pseudoscalar states.

Total error contours (including systematic uncertainties) expected in the determination of the basic Higgs-boson couplings from the combined analysis of LHC, LC and Photon Collider data are shown in Figure 6, for $M_H = 250$ GeV. Errors obtained for model with CP-violation (Φ_{HA} used as a model parameter) are only slightly larger than for CP-conserving case ($\Phi_{HA} = 0$). Values of the expected total errors on the basic Higgs-boson couplings and on the $H-A$ mixing angle Φ_{HA} (lower plot), are shown in Figure 7, 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 0.033 and 0.12 respectively. The $H-A$ mixing angle Φ_{HA} can be determined with an average error of about 150 mrad. Largest errors are obtained in the low χ_V region, $\chi_V < 0.3$, and for $\chi_V \approx \chi_u$, when large contribution from $b\bar{b}$ decays is expected. For other coupling values, in most of the considered parameter space, mixing angle Φ_{HA} can be measured to better than 100 mrad.

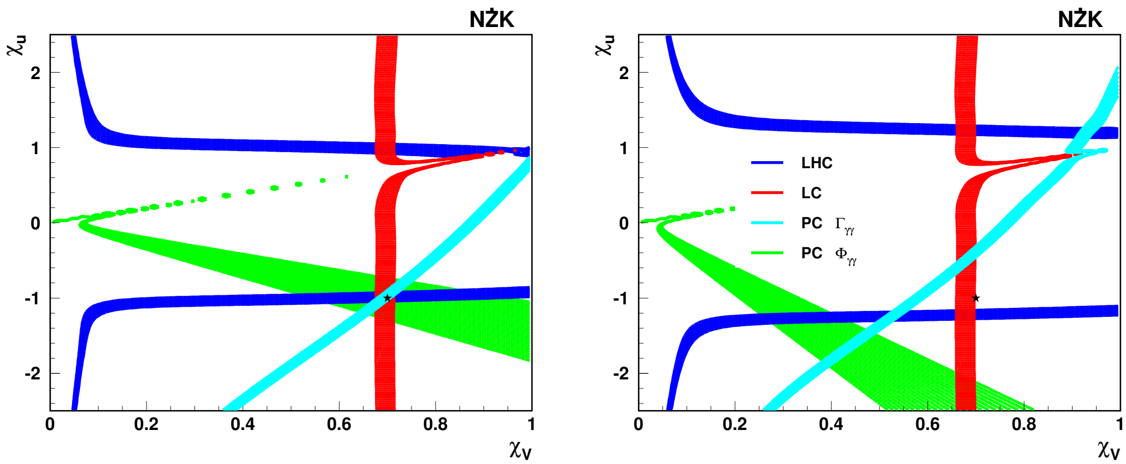

Figure 5: Complementarity of LHC, LC and Photon Collider data in the determination of the basic Higgs-boson couplings to vector bosons (χ_V) and up fermions (χ_u). Color bands show values of CP-conserving 2HDM (II) couplings consistent (on 1σ statistical error level) with cross section measurement at LHC (blue), LC (red), Photon Collider (cyan) and the phase $\phi_{\gamma\gamma}$ measurement (green). Higgs-boson h_2 with $\chi_V = 0.7$, $\chi_u = -1.0$ (star) and mass of 250 GeV is considered, without (left plot, $\Phi_{HA} = 0$) and with (right plot, $\Phi_{HA} = -0.2$) CP-violation.

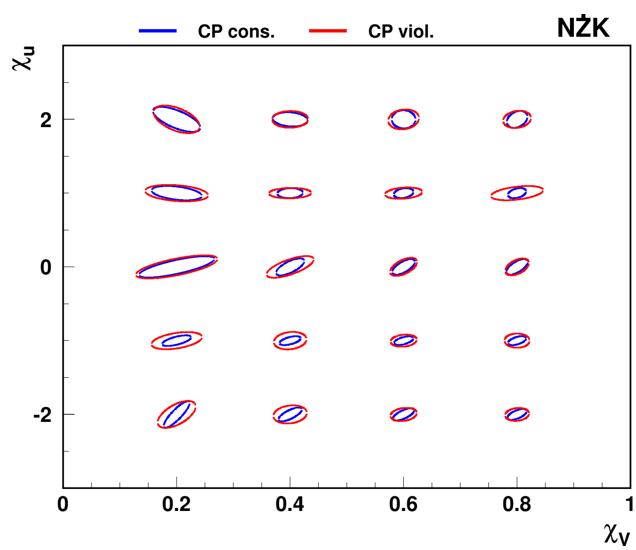

Figure 6: Expected total error contours (1σ) in the determination of the basic Higgs-boson couplings to vector bosons (χ_V) and up fermions (χ_u) from combined fit to invariant mass distributions measured at LHC, LC and Photon Collider, for the CP-conserving (blue) and CP-violating (red) 2HDM (II). Production and decays of heavy Higgs boson are considered for $M_H = 250$ GeV.

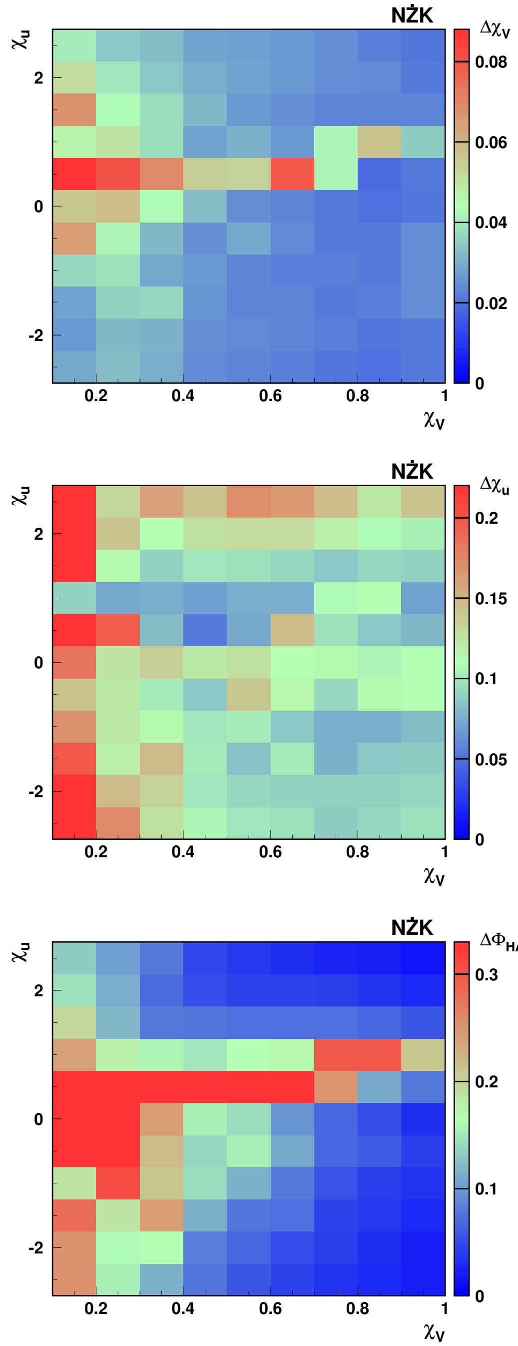

Figure 7: Expected total errors on the basic Higgs-boson couplings to vector bosons χ_V (upper plot) and up fermions χ_u (middle plot), and on the $H-A$ mixing angle Φ_{HA} (lower plot), from combined fit to invariant mass distributions measured at LHC, LC and Photon Collider, for heavy Higgs boson mass $M_H = 250$ GeV and $\Phi_{HA} = 0$.

6 Summary

The feasibility of measuring the basic Higgs-boson couplings at the the Photon Collider at TESLA has been studied in detail, using realistic luminosity spectra and detector simulation, for masses of Higgs bosons between 200 and 300 GeV. For the CP-conserving Two Higgs Doublet Model (II), basic Higgs-boson couplings to vector bosons, χ_V, and to up-type fermions, χ_u, can be determined with the error of about or below 0.1 and 0.4, respectively, for most of the considered coupling values. Cross section measurements at Photon Collider are complementary to those at LHC and LC, as they are sensitive to different combinations of Higgs-boson couplings. For general Two Higgs Doublet Model (II) with CP violation, only the combined analysis of LHC, LC and PC 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.

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References

[1] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo and V. I. Telnov, Pizma ZhETF 34, 514 (1981), JETP Lett. 34, 491 (1982); Preprint INP 81-50, Novosibirsk, 1981 and Nucl. Instrum. Meth. A 205, 47 (1983); Preprint INP 81-102, Novosibirsk, 1981;
I. F. Ginzburg, G. L. Kotkin, S. L. Panfil, V. G. Serbo and V. I. Telnov, Nucl. Instrum. Meth. A219, 5 (1984);
V. I. Telnov, Nucl. Instrum. Meth. A294, 72 (1990).

[2] P.Nieżurawski, A.F.Żarnecki, M.Krawczyk, JHEP 0211 (2002) 034 [hep-ph/0207294]

[3] B. Badelek et al., *Photon Collider at TESLA*, TESLA Technical Design Report, Part 6, Chapter 1, DESY-2001-011, ECFA-2001-209, DESY-TESLA-2001-23, DESY-TESLA-FEL-2001-05, March 2001, hep-ex/0108012.

[4] I. F. Ginzburg and I. P. Ivanov, *Phys. Lett.* B408 (1997) 325.

[5] G.J. Gounaris, J. Layssac, P.I. Porfyriadis, F.M. Renard, *Eur.Phys.J.* C13 (2000) 79.

[6] G.J. Gounaris, P.I. Porfyriadis and F.M. Renard, *Eur. Phys. J.* C19 (2001) 57.

[7] E. Asakawa, J. i. Kamoshita, A. Sugamoto and I. Watanabe, *Eur. Phys. J.* C14 (2000) 335; E. Asakawa, S. Y. Choi, K. Hagiwara and J. S. Lee, *Phys. Rev.* D62 (2000) 115005.

[8] E. Asakawa and K. Hagiwara, Eur. Phys. J. C31 (2003) 351.

[9] P.Nieżurawski, A.F.Żarnecki, M.Krawczyk, hep-ph/0403138.

[10] I. F. Ginzburg, M. Krawczyk and P. Osland, *Nucl. Instrum. Meth.* A472:149, 2001 [hep-ph/0101229]; hep-ph/0101331; hep-ph/0101208.

[11] I. F. Ginzburg, M. Krawczyk and P. Osland, *Two-Higgs-doublet models with CP violation*, presented at International Workshop on Linear Colliders (LCWS 2002), Jeju Island, Korea, August 2002, hep-ph/0211371.

[12] A.F. Żarnecki, Acta Phys.Polon. B34 (2003) 2741 [hep-ex/0207021], http://info.fuw.edu.pl/~zarnecki/compaz/compaz.html

[13] V. I. Telnov *Nucl. Instrum. Meth.* A 355 (1995) 3; V. I. Telnov, *A Code for the simulation of luminosities and QED backgrounds at photon colliders*, talk presented at Second Workshop of ECFA-DESY study, Saint Malo, France, April 2002.

[14] G.Belanger, F.Boudjema, Phys. Lett. B288 (1992) 210; D.A.Morris, et al., Phys. Lett. B323 (1994) 421.

[15] T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin, *Comp. Phys. Comm.* 135 (2001) 238.

[16] M. Pohl, H. J. Schreiber, DESY-99-030.

[17] C.P.Buszello, I.Fleck, P.Marquard, J.J. van der Bij, Eur. Phys. J. C32 (2004) 209.

[18] N.Meyer, Eur. Phys. J. C35 (2004) 171.

[19] R. Kinnunen, "Higgs physics at the LHC," in: *Proceedings of the 10th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY02)*, Eds. P. Nath, P. M. Zerwas, and C. Grosche, DESY, Hamburg, Germany, 2002.

[20] D.J. Miller, S.Y. Choi, B. Eberle, M.M. Mühlleitner and P.M. Zerwas, Phys. Lett. B505 (2001) 149;
S.Y.Choi, D.J.Miller, M.M.Muhlleitner and P.M.Zerwas, Phys. Lett. B553 (2003) 61;
C. P. Buszello, P. Marquard and J. J. van der Bij, hep-ph/0406181;
M.T.Dova, S.Ferrari, hep-ph/0406313;
R. M. Godbole, S. Kraml, M. Krawczyk, D. J. Miller, P. Nieżurawski and A. F. Żarnecki, hep-ph/0404024;
P.Nieżurawski, A.F.Żarnecki, M.Krawczyk, ICHEP'2004, abstract #12-0739.