

## CP Studies of the Higgs Sector:

### A contribution to the LHC / LC Study Group document\*

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#### Abstract

The CP structure of the Higgs sector will be of great interest to future colliders. The measurement of the CP properties of candidate Higgs particles will be essential in order to distinguish models of electroweak symmetry breaking, and to discover or place limits on CP-violation in the Higgs sector. In this report we briefly summarize various methods of determining the CP properties of Higgs bosons at different colliders and identify areas where more study is required. We also provide an example of a synergy between the LHC, an  $e^+e^-$  Linear Collider and a Photon Collider, for the examination of CP-violation in a Two-Higgs-Doublet-Model.

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# 1 Introduction

Discovery of the Higgs boson will be one of the primary goals of the next generation of colliders. If, as hoped, one or more ‘‘Higgs boson like’’ particles are observed, the next task will be to measure their masses and quantum numbers and identify whether they are the Higgs bosons of the Standard Model (SM), a Two-Higgs-Doublet-Model (2HDM), the Minimal Supersymmetric Standard Model (MSSM), or some more exotic alternative. In particular, the CP quantum numbers of the Higgs boson(s) provide good discrimination, and consequently CP studies in the Higgs sector will be a major focus when the physics programme of the LHC [1,2], an  $e^+e^-$  Linear Collider [3] or a Photon Collider [4] is mature. Such studies of the CP properties of the Higgs sector will involve establishing the CP eigenvalue(s) for the Higgs state(s) if CP is conserved, and measuring the mixing between the CP-even and CP-odd states if it is not. CP violation in the Higgs sector [5], possible in multi-Higgs models, is indeed an interesting option to generate CP violation beyond that of the SM, possibly helping to explain the observed Baryon Asymmetry of the Universe [6].

In order to identify the CP nature of a Higgs boson, one must probe the structure of its couplings to known particles, in either its production or decay. At tree level, the couplings of a neutral Higgs boson  $\phi$ , which may or may not be a CP eigenstate,<sup>†</sup> to fermions and vector bosons can be written as

$$f\bar{f}\phi : -\bar{f}(v_f + ia_f\gamma_5)f \frac{gm_f}{2m_W}, \quad VV\phi : c_V \frac{gm_V^2}{m_W} g_{\mu\nu} \quad (1)$$

where  $g$  is the usual electroweak coupling constant;  $v_f$ ,  $a_f$  give the Yukawa coupling strength relative to that of a SM Higgs boson, and  $c_V$  ( $V = W, Z$ ) are the corresponding relative couplings to gauge bosons<sup>‡</sup>. In the SM, for a CP-even Higgs  $v_f = c_V = 1$  and  $a_f = 0$ . A purely CP-odd Higgs boson has  $v_f = c_V = 0$  and  $a_f \neq 0$ , with the magnitude of  $a_f$  depending on the model. In CP-violating models,  $v_f$ ,  $a_f$  and  $c_V$  may all be non-zero at tree level. In particular, in the case of a general 2HDM or the MSSM with CP violation, there are three neutral Higgs bosons  $\phi_i$ ,  $i = 1, 2, 3$ , which mix with each other and share out between them the couplings to the  $Z$ ,  $W$  and fermions; various sum rules are given in [7–9]. Due to this fact, limits on the MSSM (and 2HDM) Higgs sector implied by LEP data are strongly affected by the presence of CP violation [8, 10, 11].

In most formulations of CP-violating Higgs sectors [9, 10, 12–15] the amount of CP mixing is small, being generated at the loop level, with only one of the couplings to gauge bosons or fermions sizable. In most cases, the predicted CP mixing is also a function of the CP-conserving parameters of the model, along with the CP-violating phases.<sup>§</sup> Thus observation and measurement of this mixing at the LC may give predictions for LHC physics; for instance for sparticle phenomenology in the MSSM. Moreover, experiments at different colliders have different sensitivities to the various couplings of eq. 1. Hence a combination of LHC, LC and photon collider (PLC) measurements of both CP-even and CP-odd variables may be necessary to completely determine the coupling structure of the

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<sup>†</sup>For CP eigenstates, a pure scalar will be denoted by  $H$  and a pure pseudoscalar by  $A$ . Otherwise we use the generic notation  $\phi$ .

<sup>‡</sup>In principle, the  $VV\phi$  coupling could also contain an additional pseudoscalar coupling, although this is absent in the SM and 2HDMs at tree-level (see later).

<sup>§</sup>For the MSSM with explicit CP violation, computational tools for the Higgs sector are available [16, 17].

Higgs sector. These are two ways in which the high potential of LHC-LC synergy for CP studies can be realised.

In what follows, we give an overview of the LHC, LC, and PLC potentials for CP studies in the Higgs sector. An example of the LHC-LC synergy is presented as well.

## 2 CP Studies at the LHC

There are several ways to study the CP nature of a Higgs boson at the LHC. In the resonant s-channel process  $gg \rightarrow \phi \rightarrow f\bar{f}$ , the scalar or pseudoscalar nature of the Yukawa coupling gives rise to  $f\bar{f}$  spin-spin correlations in the production plane [18]. A more recent study [19] looks at this process in the context of a general 2HDM.

In the process  $gg \rightarrow t\bar{t}\phi$ , the large top-quark mass enhances the  $v^2 - a^2$  contribution, allowing a determination of the CP-odd and CP-even components of a light Higgs Boson [20,21]. While this method should provide a good test for verifying a pure scalar or pseudoscalar, examination of a mixed CP state would be far more challenging, requiring  $600 \text{ fb}^{-1}$  to distinguish an equal CP-even/CP-odd mixture at  $\sim 1.5\sigma$  [20].

Higgs decay into two real bosons,  $\phi \rightarrow ZZ$ , with  $Z \rightarrow l^+l^-$ , [22,23] can be used to rule out a pseudoscalar state by examining the azimuthal or polar angle distributions between the decay lepton pairs. Below the threshold,  $\phi \rightarrow Z^*Z$ , extra information is provided by the threshold behaviour of the virtual  $Z$  boson invariant mass spectrum. This way, one could rule out a pure  $0^-$  state at  $> 5\sigma$  with  $100 \text{ fb}^{-1}$  in the SM. An extension of these studies to scalar-pseudoscalar mixing is under progress.

In weak boson fusion, the Higgs boson is produced in association with two tagging jets,  $qq \rightarrow W^+W^-qq \rightarrow \phi qq$ . As with the decay to  $ZZ$ , the scalar and pseudoscalar couplings lead to very different azimuthal distributions between the two tagging jets [24]. A similar idea may be employed in  $\phi + 2jets$  production [25] in gluon fusion. Higher order corrections [26] may, however, reduce this correlation effect strongly.

Another approach uses the exclusive (inclusive) double diffractive process  $pp \rightarrow p + \phi + p$  ( $pp \rightarrow X + \phi + Y$ ) [27–29] with large rapidity gaps between the  $\phi$  and the (dissociated) protons. The azimuthal angular distribution between the tagged forward protons or the transverse energy flows in the fragmentation regions reflect the CP of the  $\phi$  and can be used to probe CP mixing. This process is particularly promising for the region  $m_\phi < 60 \text{ GeV}$ , in which a Higgs signal may have been missed at LEP due to CP violation.

## 3 CP Studies at an $e^+e^-$ Linear Collider

In  $e^+e^-$  collisions, the main production mechanisms of neutral Higgs bosons  $\phi$  are (a) Higgsstrahlung  $e^+e^- \rightarrow Z\phi$ , (b)  $WW$  fusion  $e^+e^- \rightarrow \phi\nu\bar{\nu}$ , (c) pair production  $e^+e^- \rightarrow \phi_i\phi_j$  ( $i \neq j$ ) and (d) associated production with heavy fermions,  $e^+e^- \rightarrow f\bar{f}\phi$ . Studies of CP at the Linear Collider aim at extracting the relevant couplings mentioned in eq. 1. Recall that a pure pseudoscalar of the 2HDM or MSSM does not couple to vector bosons at tree level. The observation of all three  $\phi_i$  ( $i = 1, 2, 3$ ) in a given process, e.g.  $e^+e^- \rightarrow Z\phi_{1,2,3}$ , therefore represents evidence of CP violation [30–32].

In the Higgsstrahlung process, if  $\phi$  is a pure scalar the  $Z$  boson is produced in a state of longitudinal polarization at high energies [33, 34]. For a pure pseudoscalar, the process proceeds via loops and the  $Z$  boson in the final state is transversally polarized. The

angular distribution of  $e^+e^- \rightarrow ZH$  is thus  $\propto \sin^2\theta_Z$ , where  $\theta_Z$  is the production angle of the  $Z$  boson w.r.t. to the beam axis in the lab frame, while that of  $e^+e^- \rightarrow ZA$  is  $\propto (1 + \cos^2\theta_Z)$ . A forward-backward asymmetry would be a clear signal of CP violation. Furthermore, angular correlations of the  $Z \rightarrow f\bar{f}$  decay can be used to test the  $J^{PC}$  quantum numbers of the Higgs boson(s). Measurements of the threshold excitation curve can give useful additional information [35,36]. A study in [3] parametrised the effect of CP violation by adding a small  $ZZA$  coupling with strength  $\eta$  to the SM matrix element,  $\mathcal{M} = \mathcal{M}_{ZH} + i\eta\mathcal{M}_{ZA}$ , and showed that  $\eta$  can be measured to an accuracy of 3.2% with  $500 \text{ fb}^{-1}$ .

Angular correlations of Higgs decays can also be used to determine the CP nature of the Higgs boson(s), independent of the production process; see [37–39] and references therein. The most promising channels are  $\phi \rightarrow \tau^+\tau^-$  ( $m_\phi < 2m_W$ ) and  $\phi \rightarrow t\bar{t}$  ( $m_\phi > 2m_t$ ) which in contrast to decays into  $WW$  or  $ZZ$  allow equal sensitivity to the CP-even and CP-odd components of  $\phi$ .

A detailed simulation of  $e^+e^- \rightarrow ZH$  followed by  $H \rightarrow \tau^+\tau^-$  and  $\tau^\pm \rightarrow \rho^\pm\bar{\nu}_\tau(\nu_\tau)$  [40–42] showed that CP of a 120 GeV SM-like Higgs boson can be measured to  $\geq 95\%$  C.L. at a 500 GeV  $e^+e^-$  LC with  $500 \text{ fb}^{-1}$  of luminosity. In case of CP violation, the mixing angle between the scalar and pseudoscalar states may be determined to about 6 degrees [43], the limiting factor being statistics.

## 4 CP Studies at a Photon Collider

A unique feature of a PLC is that two photons can form a  $J_z = 0$  state with both even and odd CP. As a result a PLC has a similar level of sensitivity for both the CP-odd and CP-even components of a CP-mixed state:

$$\text{CP-even} : \epsilon_1 \cdot \epsilon_2 = -(1 + \lambda_1\lambda_2)/2, \quad \text{CP-odd} : [\epsilon_1 \times \epsilon_2] \cdot k_\gamma = \omega_\gamma i\lambda_1(1 + \lambda_1\lambda_2)/2, \quad (2)$$

$\omega_i$  and  $\lambda_i$  denoting the energies and helicities of the two photons respectively; the helicity of the system is equal to  $\lambda_1 - \lambda_2$ . This contrasts the  $e^+e^-$  case, where it is easy to discriminate between CP-even and CP-odd particles but may be difficult to detect small CP-violation effects for a dominantly CP-even Higgs boson [44]. For the PLC, one can form three polarization asymmetries in terms of helicity amplitudes which give a clear measure of CP mixing [45]. In addition, one can use information on the decay products of  $WW$ ,  $ZZ$ ,  $t\bar{t}$  or  $b\bar{b}$  coming from the Higgs decay. Furthermore, with circular beam polarization almost mass degenerate (CP-odd)  $A$  and (CP-even)  $H$  of the MSSM may be separated [46–48].

A measurement of the spin and parity of the Higgs boson may also be performed using the angular distributions of the final-state fermions from the  $Z$  boson decay, which encode the helicities of  $Z$ 's. A detailed study was performed for above and below the  $ZZ$  threshold in [22]. A realistic simulation based on this analysis was made recently in [49].

The same interference effects as mentioned above can be used in the process  $\gamma\gamma \rightarrow \phi \rightarrow t\bar{t}$  [50,51] to determine the  $t\bar{t}\phi$  and  $\gamma\gamma\phi$  couplings for a  $\phi$  with indefinite CP parity.

## 5 Example of LHC-LC synergy

As an example of the LHC-LC synergy, we consider the SM-like, type II 2HDM with CP-violation [49,52]. We study production of  $\phi_2$  in the mass range 200 to 350 GeV, decaying

to  $VV$ ,  $V = W/Z$ , at the LHC, LC and PLC. In particular, we investigate the interplay of different experiments for the determination of  $\tan\beta$  and the CP mixing angle  $\Phi_{HA}$ .

Figure 1 shows the expected rates for  $\phi_2$  with  $m_{\phi_2} = 250$  GeV relative to the SM ones, as a function of  $\tan\beta$  and  $\Phi_{HA}$ . For a SM Higgs boson, the expected precision on  $\sigma \times BR(H \rightarrow VV)$  is  $\sim 15\%$  at the LHC [53,54] and better than 10% at a LC and PLC [55,56]. A PLC will allow to measure  $\Gamma_{\gamma\gamma}$  with a precision of 3–8% and the phase of the  $\phi \rightarrow \gamma\gamma$  amplitude,  $\Phi_{\gamma\gamma}$ , to 40 – 120 mrad [56].

Figure 2 shows the  $1\sigma$  bands for determination of  $\tan\beta$  and  $\Phi_{HA}$ , at the LHC, LC and PLC for a particular choice of parameters:  $\tan\beta = 0.7$  and  $\Phi_{HA} = -0.2$ . The chosen point is indicated by a star. For the PLC, information from  $\Gamma_{\gamma\gamma}$  and  $\Phi_{\gamma\gamma}$  is included. As can be seen, an accurate determination of both parameters of the model requires a combination of data from all three colliders.

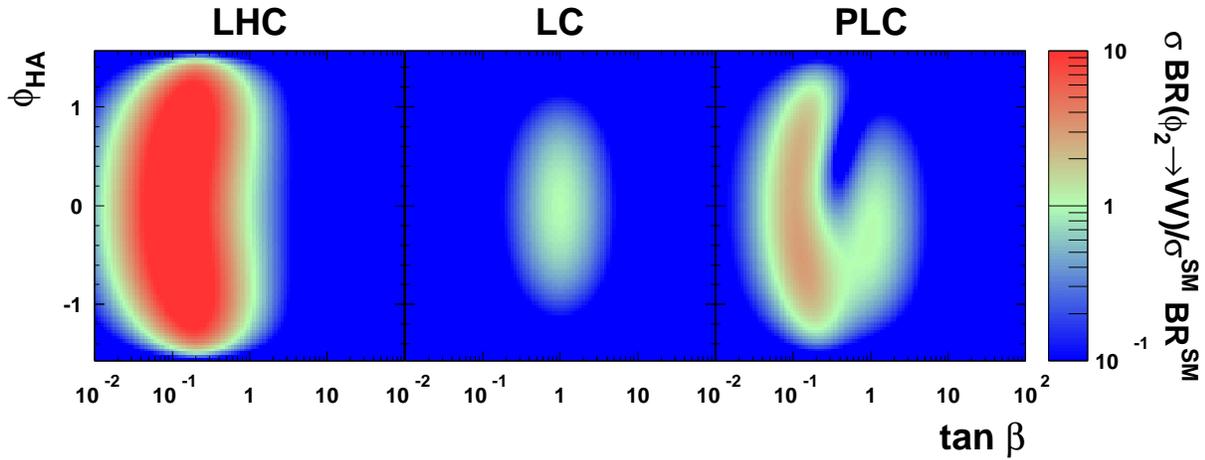


Figure 1:  $\sigma \times BR$  for  $\phi_2 \rightarrow VV$  with  $V = W/Z$ , relative to the SM expectation, for a mass of 250 GeV, as a function of  $\tan\beta$  and  $\Phi_{HA}$  for the LHC, LC and PLC.

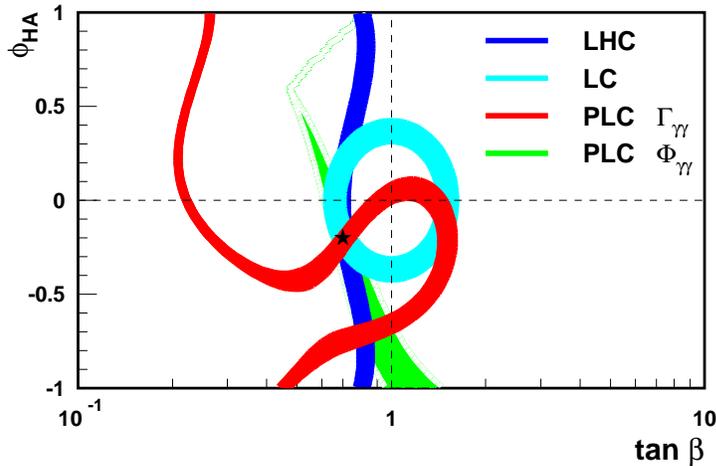


Figure 2:  $1\text{-}\sigma$  bands for the determination of  $\tan\beta$  and  $\Phi_{HA}$  from measurements at the LHC, LC and PLC, for the case  $\tan\beta = 0.7$  and  $\Phi_{HA} = -0.2$ . The assumed parameter values are indicated by a star ( $\star$ ).

## 6 Summary

The LHC, an  $e^+e^-$  LC, and a LC in the photon collider option (PLC) will be able to provide important information on the CP quantum numbers of the Higgs boson(s). We have summarised the potentials of the different colliders in this document and discussed the possible LHC-LC synergy.

In the MSSM, for instance, the size of CP-violating effects in the Higgs sector depends in part on the sparticle spectrum. Observation and measurement of Higgs-sector CP mixing at the LC can hence give predictions for phenomenology at the LHC in the CP-conserving sector, thus providing a high potential of LHC-LC synergy. A detailed study of this issue is, however, still missing.

Moreover, experiments at different colliders have different sensitivities to the various couplings of eq. 1. Hence a combination of LHC and LC/PLC measurements of both CP-even and CP-odd variables may be necessary to completely determine the coupling structure of the Higgs sector. In this document we have presented a first analysis which exemplifies this realisation of LHC-LC synergy. While the example presented shows a high potential of the LHC-LC synergy for CP studies, detailed realistic simulations still need to be performed.

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