Measuring the CP properties of the Higgs sector at electron-positron colliders

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The violation of CP symmetry at the electro-weak scale is one of the essential ingredients for electro-weak baryogenesis. It is therefore of great interest to map the CP properties of the Higgs sector in as much detail as possible. A linear electron-positron Higgs factory collider will provide many opportunities to probe the CP nature of the Higgs sector, thanks to access to several Higgs production processes at a wide range of centre-of-mass energies.

In this paper we report on two studies based on full simulation of detector response and realistic reconstruction algorithms: 1) a study of $h \rightarrow \tau \tau$ at ILC-250, in which mixing of CP eigenstates can be measured to a precision of 75 mrad; and 2) the current status of an ongoing study of the ZZ-fusion process at 1.4 TeV CLIC and 1 TeV ILC, for which we expect to achieve concrete results during the Snowmass study period.

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I. INTRODUCTION

The violation of CP symmetry at the electro-weak scale is one of the essential ingredients for electro-weak baryogenesis. It is therefore of great interest to map the CP properties of the Higgs sector in as much detail as possible.

CP violation in the Higgs sector can be probed in both the fermionic and bosonic couplings of the Higgs boson. To cover the various measurements, it is highly advantageous to utilize collisions at a wide range of centre-of-mass energies. Linear electron-positron "Higgs factory" colliders, with their inherent extendibility in energy, provide the ability to carry out a complete survey of the sector.

In this paper we discuss the measurement of CP effects in $h \to \tau \tau$ in 250 GeV collisions at ILC [1], where the analysis profits from the experimental advantages of the Higgs-strahlung process [2]. We also discuss the ZZ-fusion production process, which provides a powerful tool to probe the bosonic coupling. The ZZ-fusion cross-section is tiny at 250 GeV but grows with energy, so a high energy collider is imperative. We report on the status of ongoing studies at 1.4 TeV CLIC and 1 TeV ILC.

High energy collisions above ~ 550 GeV also allow measurement of the top-quark's Yukawa coupling in the process $e^+e^- \rightarrow t\bar{t}h$; we leave a detailed study of this channel's CP sensitivity as a future exercise for the interested reader.

II. INTERNATIONAL LARGE DETECTOR AND CLIC DETECTOR

The studies presented here are based on detailed Geant-4 simulations of ILC's International Large Detector concept (ILD) [4] and the CLIC-ILD concept [5]. To meet the strict requirements to maximize the physics output at these facilities, these detectors are designed with an ultraprecise and light-weight vertex detector, a high-precision low mass tracking system based on a TPC complemented with silicon layers operating in a 3.5-4 T magnetic field, and calorimeters with highly segmented readout to enable optimal particle flow reconstruction. Almost the entire 4π solid angle around the collision point is covered by active detectors. Such detectors can provide impact parameter resolution of $\sim 3 \ \mu m$ and resulting excellent jet flavor tagging, track momentum resolution at high momentum of $\delta p_T/p_T \sim 3 \times 10^{-5} p_T$, and jet energy resolution of 3 - 4% over a wide range of jet energies.

Signal and background processes are generated using the WHIZARD event generator [6, 7]

taking into account the accelerators' beam parameters, including such effects as beamstrahlung and initial state radiation. Generated events are then passed through detailed Geant4 [9] models of the detectors, described using tools provided by DD4hep [10]. The energy deposits calculated in the Geant4 simulation are digitised and reconstructed using the tools provided in the ilcsoft software framework [11], including particle flow reconstruction by PandoraPFA [12].

III. CP MEASUREMENT IN $h\tau\tau$ AT ILC-250

CP violation in the tau lepton's Yukawa coupling can explicitly be introduced by a Lagrangian term such as

$$\mathcal{L}_{\mathrm{H}\tau\tau} = g\overline{\tau}(\cos\psi_{\mathrm{CP}} + i\gamma_5\sin\psi_{\mathrm{CP}})\tau\mathrm{H} \tag{1}$$

which is CP-conserving for $\psi_{\rm CP} = 0$ and maximally violates CP for $\psi_{\rm CP} = \pi/2$. The CP nature of the tau-pair produced in Higgs decay is reflected in the correlation between the transverse tau spin components, and thereby in the relative distribution of the taus' decay products. This analysis demonstrates how to reconstruct the tau spin orientation from its decay products, and to extract the relative CP even and odd contributions in a sample of $h \to \tau \tau$ events.

An optimal tau polarimeter, or spin orientation estimator, is easy to define in decays to one or two pions, which together account for around 36% of tau decays. Considering the Higgs rest frame, the CP sensitive observable $\Delta \phi$ is defined as the difference in azimuthal angle, defined with respect to the tau momentum direction, between the two polarimeters. The distribution of events in $\Delta \phi$ is sinusoidal, with a phase which is sensitive to the admixture of even and odd CP components. Examples of distributions of this CP-sensitive observable at different CP mixing angles ψ_{CP} are shown in Fig.1.

A. Analysis in ILD

We here summarize the analysis described in [3]. The signal process is $e^+e^- \rightarrow ZH$, with subsequent decay of the Z boson to electrons, muons, or hadrons, and of the Higgs boson to a pair of tau leptons. The signal tau leptons are decayed by Pythia8 [8] into the one- and two-pion decay channels, taking spin correlations into account. Considered backgrounds include two- and four-fermion final states, and well as other decay modes of the Higgs-strahlung process.



FIG. 1. Distributions of events in $\Delta \phi$, integrated over θ^{\pm} , at MC truth level, for different values of $\psi_{\rm CP}$ [3].

B. Tau lepton reconstruction

We here outline the tau reconstruction procedure described in [13]. Each tau lepton in the final state decays to at least one neutrino which escapes detection. To optimally reconstruct polarimeters and CP mixing, this neutrino momentum should be reconstructed. Assuming that both taus decay hadronically, there are 6 unmeasured quantities per event, corresponding to the 3-momenta of the event's two neutrinos. By considering the measured momenta of visible tau decay products, their impact parameters with respect to the reconstructed tau production vertex, and imposing constraints on the reconstructed tau mass and the transverse momentum of the di-tau system, the neutrino momenta can be reconstructed up to a 4-fold ambiguity, which can be resolved in many cases by considering the reconstructed tau lifetime.

C. Event selection

Kinematic observables, for example the di-tau invariant mass, the mass recoiling against the Z decay products, and the angle between the total event momentum and the beam axis, were used to select an event sample enriched in signal events. Three different channels were considered, according to the Z boson decay into electrons, muons, or hadrons. Assuming a total integrated luminosity of 2/ab at ILC-250, a few tens of events are expected in the case of Z decays to electrons and muons, with a signal-to-background ration of around 1:5. For hadronic Z decays, over 500 signal events are expected after selection, but with much larger background contamination.

The tau decay mode is reconstructed by considering the number of reconstructed charged hadrons and photons within the candidate tau jet, as well as the invariant mass of various group-



FIG. 2. Distributions of reconstructed $\Delta \phi$ in the "gold" (group A) and "silver" (group B) categories, for events selected in the hadronic Z decay channel. The distribution of signal events is shown as open red circles, and the total background distribution as filled blue triangles. Signal samples were generated with $\psi_{CP} = 0$ (i.e. the SM) [3].

ings of those particles. The efficiency to correctly identify both tau decay modes in a selected event ranges between 87% and 94%, depending on both the Z and tau decay modes.

D. CP sensitivity

At this stage the tau polarimeters can be calculated from the tau decay products' momenta boosted into the tau rest frames. Events are classified according to their expected sensitivity to CP effects, depending on the orientation of the polarimeter with respect to the tau momentum, the quality of the impact parameter reconstruction, encoded by its significance, and the expected contamination both from background processes and mis-identified tau decay modes. Four classes are defined, which in this Olympic year we label as "gold", "silver", "bronze" and "the rest", in each of which the CP-sensitive observable $\Delta \phi$ is fitted using a maximum likelihood fit to extract the CP mixing parameter, as shown in Fig. 2.

In the case of 1/ab of data with unpolarized beams, the expected sensitivity on the CP mixing angle $\delta \psi_{CP}$ is 116 mrad, dominated by events with hadronic Z decay and with at least one tau decay to two pions. If we assume that all background can be rejected, the sensitivity improves to 76 mrad, while if in addition all signal events are selected and polarimeters are perfectly reconstructed, the ultimate sensitivity is 25 mrad.

Considering the 2/ab expected at ILC in various beam polarisation combinations, the expected sensitivity on $\delta\psi_{\rm CP}$ is 75 mrad when all experimental effects are taken into account. There is

considerable potential scope for improvement, for example by improved reconstruction and selection methods, better tau decay mode identification, and the use of additional tau decay modes.

IV. CP MEASUREMENT OF THE hZZ VERTEX

We here report on the current status of an analysis of the CP properties of the hZZ vertex, using the ZZ-fusion production in high energy electron-positron collisions at CLIC (1.4 TeV) and ILC (1 TeV).

A. CPV mixing in the Higgs sector

Let us assume that SM-like Higgs boson is a quantum superposition of CP-even (scalar) and CP-odd (pseudoscalar) states through CP violating mixing angle Ψ_{CP} . The Higgs to Z boson tensor coupling can be then described as:

$$g_{HZZ} = ig \frac{M_Z}{\cos\theta_W} (\lambda_H \cdot g^{\mu\nu} + \lambda_A \cdot \epsilon^{\mu\nu\rho\sigma} \frac{(p_1 + p_2)\rho(p_1 - p_2)\sigma}{M_Z^2})$$
(2)

where p_1 and p_2 are four-momenta of the Z bosons [14]. Contribution to gauge HZZ coupling with $\lambda_{\rm H}$ has a structure of the CP-even SM Higgs boson coupling (H), while the term with $\lambda_{\rm A}$ stands for the CP-odd, pseudoscalar coupling. Superposition of the two states can be described as:

$$h = \lambda_H \cdot H + \lambda_A \cdot A \tag{3}$$

where

$$\lambda_H = \cos \psi_{CP}$$
 and $\lambda_A = \sin \psi_{CP}$ (4)

Although we further consider Higgs to $b\bar{b}$ decays in order to minimize the list of possible backgrounds for this particular event topology, we do not make specific assumptions on Higgs couplings to fermions, thereby preserving the model independency.

B. Sensitive observables

We are considering Higgs boson production in ZZ-fusion $e^+e^- \rightarrow e^+e^-H(H \rightarrow b\bar{b})$, with the 2-jet and two electron spectators experimental signature. According to [15], there are several observables sensitive to the mixing from Eq. 4. We further use the angle $\Delta \Phi$ between production planes (Fig. 3 and Eq. 5).



FIG. 3. Illustration of the CP sensitive angle $\Delta \Phi$ in the ZZ fusion process.

$$\Delta \Phi = \arccos(\hat{n}_1 \cdot \hat{n}_2) \tag{5}$$

where

$$a = \frac{q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)|}, \qquad \hat{n}_1 = \frac{q_{e^-_i} \times q_{e^-_f}}{|q_{e^-_i} \times q_{e^-_f}|} \qquad \text{and} \qquad \hat{n}_2 = \frac{q_{e^+_i} \times q_{e^+_f}}{|q_{e^+_i} \times q_{e^+_f}|} \tag{6}$$

and q stands for the corresponding momenta, while $\hat{n}_{1,2}$ define unit vectors orthogonal to the production planes. Parameter *a* defines how the second (positron) plane is rotated w.r.t. the first (electron) plane. If it falls backwards (as illustrated in Fig. 3) a = -1 otherwise a = 1. Direction of Z boson in the electron plane regulates the notion of direction (forward or backward) by the right hand rule.

C. Event samples

Signal event samples of approximately 8000 events, corresponding to a nominal integrated luminosity of 2.5 ab^{-1} , are reconstructed at 1.4 TeV CLIC, while about 1000 events at 1 TeV ILC are considered, corresponding to only 1/3 of the expected signal statistics in $1 ab^{-1}$ of data. The full

detector simulation, including realistic luminosity spectrum and overlay of beamstrahlung background is applied in both experiments.

Several background processes with similar final state as the signal are considered, where the major contribution comes from backgrounds with large cross-sections, such as $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow e\nu qq$.

D. Method

The method of both analyses is the same:

- 1. It starts with the isolation of electron spectators in the tracking volume, requiring two isolated leptons per event. The simulation, reconstruction and analyses are carried out with the ILCDIRAC framework [16]. Electron isolation is optimized according to track energy, the ratio of energies deposited in the electromagnetic and hadronic calorimeters, as well as the impact parameters of the electron track. Electron tracks are required to satisfy two-dimensional requirements on cone energy vs. electron energy, where the cone energy sums up all particle energies excluding the electron itself, in a cone of optimized size of few degrees around the isolated lepton track. This is achieved by employing the Isolated Lepton Finder Marlin processor [17].
- 2. In order to separate signal from background events, multivariate analyses (MVA) based on TMVA toolkit [18] is employed. Several sensitive observables are used as input to MVA, like reconstructed Higgs mass and energies of the final electrons. Due to specific properties of the 2e 2-jet final state, considered background is highly suppressed in both ILC and CLIC study, up to a percent level compared to the signal in the CLIC case. Although limited in statistics compared to the inclusive Higgs production in ZZ-fusion, this approach enables: a) combination with other Higgs decay channels (i.e. H → WW) to improve statistical precision, b) almost background free samples simplifying the method in terms of a background fit, at least at CLIC.
- 3. Upon obtaining reconstructed $\Delta \Phi$ distributions, $\Psi_{\rm CP}$ is extracted from the fit of a single (pseudo) experiment. All simulations are done for $\Psi_{\rm CP} = 0$ that is assuming pure state of the SM Higgs boson H. The fit correctly reproduce generated distributions for $\Psi_{\rm CP} = 0$ and $\Psi_{\rm CP} = \pi/2$ obtained using 2HDM model in WHIZARD V2.8.1 [19] within the UFO framework, as illustrated in Fig. 4.



FIG. 4. $\Delta \Phi$ distributions for $\Psi_{\rm CP} = 0$ and $\Psi_{\rm CP} = \pi/2$ corresponding to pure scalar and pseudoscalar states of the Higgs boson.

E. Status of the ongoing analyses

At 1.4 TeV CLIC we are finalizing the step 4) from the previous section, with a promising uncertainty of individual experiments of order of a few degrees for absolute statistical uncertainty of $\Psi_{\rm CP}$. At ILC, we have completed the step 2), with background suppression for a factor 10³ and CP insensitive behavior.

V. SUMMARY

Linear electron-positron colliders will enable a number of measurements sensitive to the CP nature of the Higgs sector, which is a crucial ingredient in the quest to understand the possibility of baryogenesis at the electro-weak scale. The clean experimental environment of an electron-positron collider is conducive to precision measurements of the often complex final states, while the energy-extendibility of a linear collider will allow a number of complementary measurements at different centre-of-mass energies. In this paper we have highlighted a Higgs CP measurement using the τ Yukawa coupling at 250 GeV, where mixing between CP even and odd contributions can be measured with a precisio of 75 mrad at ILC-250.

Higher energy stages, at a TeV or higher, can be used to measure CP effects in the HZZ coupling by studying the ZZ-fusion Higgs production process. We expect to provide quantitative results on this analysis during the remainder of the Snowmass study. The combination of such a suite of measurements will allow a global and complete view of the Higgs' CP nature to be established.

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- [1] P. Bambade, et al. "The International Linear Collider: A Global Project," [arXiv:1903.01629 [hep-ex]]
- [2] B. L. Ioffe and V. A. Khoze, "What Can Be Expected from Experiments on Colliding e+ e- Beams with e Approximately Equal to 100-GeV?," Sov. J. Part. Nucl. 9 (1978), 50 LENINGRAD-76-274
- [3] D. Jeans and G. W. Wilson, "Measuring the CP state of tau lepton pairs from Higgs decay at the ILC," Phys. Rev. D 98 (2018) no.1, 013007 [arXiv:1804.01241 [hep-ex]]
- [4] H. Abramowicz et al. [ILD Concept Group], "International Large Detector: Interim Design Report," [arXiv:2003.01116 [physics.ins-det]]
- [5] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, "Physics and Detectors at CLIC: CLIC Conceptual Design Report," [arXiv:1202.5940 [physics.ins-det]]
- W. Kilian, T. Ohl, J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," Eur.Phys.J.C71 (2011) 1742 [arXiv:0708.4233 [hep-ph]]
- M. Moretti, T. Ohl, J. Reuter, "O'Mega: An Optimizing matrix element generator," LC-TOOL-2001-040-rev [arXiv:hep-ph/0102195-rev]
- [8] T. Sjöstrand et al., "An Introduction to PYTHIA 8.2", Comput. Phys.Commun. 191 (2015) 159
 [arXiv:1410.3012 [hep-ph]]
- [9] S. Agostinelli et al., "Geant4—a simulation toolkit," Nucl. Instrum. Meth. A 506 (2003), 250-303
- [10] M. Frank, F. Gaede, C. Grefe and P. Mato, "DD4hep: A Detector Description Toolkit for High Energy Physics Experiments," J. Phys. Conf. Ser. 513 (2014), 022010
- [11] https://ilcsoft.desy.de/portal
- M. A. Thomson, "Particle Flow Calorimetry and the PandoraPFA Algorithm," Nucl. Instrum. Meth. A 611 (2009), 25-40
- [13] D. Jeans, "Tau lepton reconstruction at collider experiments using impact parameters," Nucl. Instrum. Meth. A 810 (2016), 51-58 [arXiv:1507.01700 [hep-ex]]
- [14] D.J. Miller, S.Y. Choi, B. Eberle, M.M. Mühlleitner and P.M. Zerwas, Phys. Lett. B505 (2001) 149 arXiv:hep-ph/0102023v2.
- [15] S. Bolognesi et al., On the spin and parity of a single-produced resonance at the LHC, Phys.Rev.D86:095031, (2012).

- [16] C. Grefe et al., ILCDIRAC, a DIRAC extension for the Linear Collider community, CLICdp-Conf 2013-003, CERN, Geneva (2013).
- [17] O. Wendt, F. Gaede, T. Kramer, Event reconstruction with MarlinReco at the ILC, Pramana 69 (2007), arXiv:physics/0702171.
- [18] A. Höcker et al., TMVA Toolkit for multivariate data analysis (2009), arXiv:physics/0703039v2.
- [19] W. Kilian, T. Ohl, J. Reuter, WHIZARD: Simulating Multi-Particle Processes at LHC and LC, Eur. Phys. J. C 71, 1742 (2011), arXiv:0708.4233v2.