Probing CPV mixing in the Higgs sector in VBF at 1 TeV ILC

Ivanka Bozovic Jelisavcic[a],[*], Natasa Vukasinovic[a] and Goran Kacarevic[a]

a VINCA Institute of Nuclear Sciences – National Institute of the Republic of Serbia
M. Petrovica Alasa 12-14, Belgrade, Serbia

E-mail: `i.boozovic@vinca.rs`, `nvukasinovic@vinca.rs`,
`kacarevicgoran@vinca.rs`

The current precision of measurements at LHC experiments cannot exclude the possibility that a Standard Model-like Higgs boson is a CP violating mixture of CP-even and CP-odd states. We have addressed that possibility here, in a full simulation of the ILD experiment at 1 TeV centre-of-mass energy ILC. Higgs interactions are probed in the HZZ vertex in vector boson fusion production of Higgs bosons. It is found that the mixing angle between states of opposite CP parities can be measured with the absolute statistical uncertainty of 3.8 mrad, for the pure scalar, corresponding to f_{CP}=1.44·10^{-5} at 68% CL.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

---

[*] Speaker

1. Introduction

The state-of-the-art of experimental measurements quantifying the CP violating effect in nature is such that 9 to 10 orders of magnitude are lacking to explain the observed baryon asymmetry of the Universe [1]. Discovery of the Higgs boson offers a new range of Higgs interactions, both with fermions and bosons, where CP symmetry could be violated. At future Higgs factories [2], most studies are done in Higgs fermionic decays (i.e. to $\tau^+\tau^-$) or in the Higgstrahlung production channel [3]. This is the first fully simulated measurement obtained in vector-boson-fusion (VBF), namely in ZZ-fusion, a sub-dominant Higgs production channel at around 1 TeV center-of-mass energy and above.

2. Measurement of the CPV mixing

Let us assume in a very generic way, similarly to indirect CP violation in K_S and K_L mesons [4], that the 125 GeV Higgs mass eigenstate *h* is a CP violating mixture of two states of opposite CP parities (H as a CP-even and A as a CP-odd state):

$$h = H \cdot \cos \Psi_{CP} + A \cdot \sin \Psi_{CP} \quad (1)$$

The question of interest is if this effect can be measured in ZZ-fusion production vertex and if so, with what statistical precision. As shown in [5], higher center-of-mass energies are required for the VBF to dominate Higgs boson production. To have ZZ-fusion statistically relevant, one needs a linear e^+e^- collider operating at around 1 TeV center-of-mass energy or above. The International Linear Collider (ILC) [6] is a candidate for a future Higgs factory with a possibility to be upgraded to a TeV energy scale. It turns out [7] that center-of-mass energies at around 1 TeV offer a favorable interplay between centrality of the ZZ-fusion events (at higher energies events are boosted below the central tracking region in a significant amount) and the Higgs production cross-section rising with $\sqrt{s}$.

2.1 Simulation

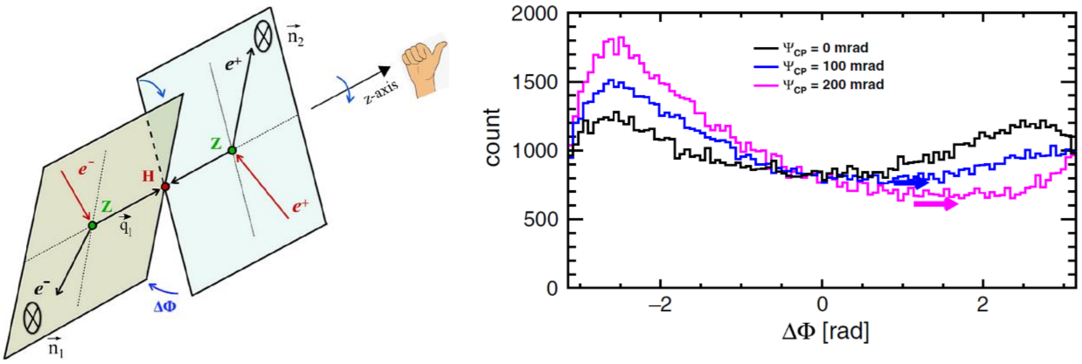
As already mentioned, Higgs boson is produced in ZZ-fusion and exclusively reconstructed in 2 b-jet decays to avoid $ee\gamma$ final state background that would othervise be present in an inclusive reconstruction. Events are generated in WHIZARD V2.8.3 [8] using the Higgs characterisation model [9] for the signal, while the Standard Model (SM) background is considered. Fast simulation DELPHES [10] of the response of the ILD detector is employed for the signal, while background is fully reconstructed in Geant 4 [11] based Mokka [12]. Number of expected events in 8 ab^{-1} of data foressen at 1 TeV ILC and number of simulated signal and background events are given in Table 1. Events are selected with the selection described in [7], with the signal efficiency of 70% and background remaining in a permille fraction of the signal (~3‰) after the selection.

2.2 Sensitive observable

To measure the mixing angle Ψ_{CP} from Eq.1, a sensitive angular abservable is established as the azimuthal angle $\Delta\Phi$ between the production planes where a z-axis is defined by the Z boson emitted by the initial electron. Definition of $\Delta\Phi$ is illustrated in Fig. 1a while its dependence on the mixing angle Ψ_{CP} is given in Fig. 1b.

Signal	σ (fb)	Expected in 8 ab^{-1}	Reconstructed MC events
$e^+e^- \to He^+e^-$; $H \to b\bar{b}$	13	104000	6×10^{5a} 3495^b
Background^b			
$e^+e^- \to q\bar{q}e^+e^-$	2.4×10^3	19×10^6	2×10^5
$e^+e^- \to qq$	3.6×10^3	29×10^6	4×10^5
$e^+e^- \to q\bar{q}e\nu$	3×10^3	24×10^6	2.6×10^6
$e^+e^- \to llll$	8×10^3	64×10^6	1.5×10^6
$e^+e^- \to eeqqqq$	37	30×10^4	1×10^4
$e^+e^- \to e\nu_e qqqq$	51	4×10^5	1×10^6
$e^+e^- \to qq\nu_e ee\nu_e$	5.6	45×10^3	5×10^4

Table 1. Simulated and expected signal and background events (*a* obtained with fast and *b* with full detector simulation).



a) b)

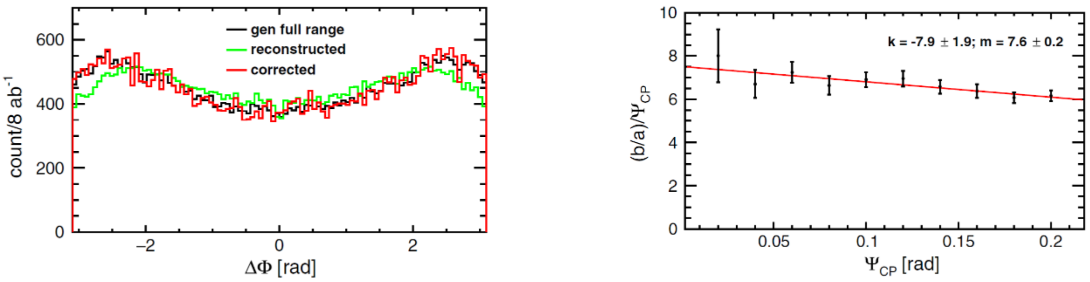
Figure 1: a) Definition of the observable ΔΦ and b) ΔΦ distribution for different mixing anglesΨ_{CP}. Arrows are illustrating the shif of the minimum towards largers values of ΔΦ occuring for the non-zero (positive) mixing angle.

The dependence of ΔΦ from the mixing angle is extracted empirically from the signal data. This is illustrated in Fig. 2 (a and b). The Fig. 2a gives comparison between generated ΔΦ distribution, reconstructed distribution and the reconstructed distribution corrected for the detector acceptance. Position of a minimum of such a distribution can be obtained from the fit of experimental data with the following function:

$$f(\Delta\Phi)=A + B \cdot cos(a \cdot \Delta\Phi - b) \qquad (2)$$

The minimum of ΔΦ is determined as *b/a* with *A*, *B*, *a* and *b* being the free parameters of the fit. The Fig. 2b illustrates $(b/a)/\Psi_{CP}$ dependence on Ψ_{CP} which is to a good approximation linear with the first and zero order coeficients *k* and *m* respectively. These coeficients should be determined from simulation. Combining the information on *a* and *b* from experimental data (in our case pseudodata) and on *k* and *m* from simultaion, Ψ_{CP} can be measured by solving the equation:

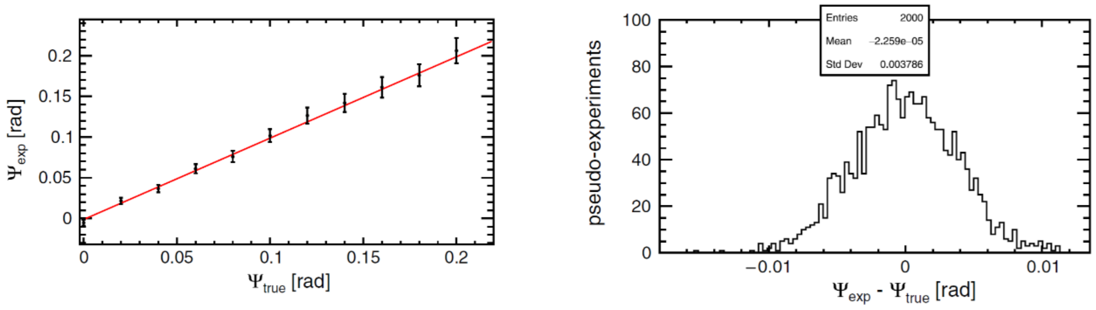
$$k \cdot \Psi^2_{CP} + m \cdot \Psi_{CP} - (b/a) = 0 \qquad (3)$$



a) b)

Figure 2: a) ΔΦ distribution for generated, reconstructed and corrected data for the detector acceptance and b) Dependence of the minimum (*b*/*a*) of ΔΦ distribution on the mixing angle Ψ_{CP}.

Fig. 3a illustrates that the mixing angle Ψ_{CP} can be retrieved in the described manner for the mixing angles up to 200 mrad. For the larger mixing, local fit of the ΔΦ minimum (Eq. 2) deteriorates and possibly another function should be employed to fit the minimum of ΔΦ.



a) b)

Figure 3: a) Measured vs. true values of the mixing angle Ψ_{CP} and b) Dissipation of the mean of the repeated measurements (pseudo experiments) of the mixing angle Ψ_{CP} for the pure scalar state.

2.3 Statistical uncertainty

In order to determine statistical dissipation of the measured mean from the true (generated) value of the mixing angle Ψ_{CP}, 2000 pseudo experiments are repeated for the pure scalar state. The result is given in Fig. 3b, illustrating the dissipation of 3.8 mrad in 1 σ range. Dissipation of the error itself is found to be 0.4 mrad [7]. In the formalism of [3], obtained result corresponds to the CP factor f_{CP} of $1.44 \cdot 10^{-5}$ being at the theoretical target of sensitivity to measure (in bosonic vertices HVV, V=Z, W) violation of CP symmetry sufficient to explain the baryon asymmetry of the Universe.

3. Summary

This is the first fully simulated measurement at an e^+e^- collider (ILC, 1 TeV), where the CP violating mixing between scalar and pseudoscalar states is determined in VBF Higgs production vertex (ZZ-fusion). It is found, assuming the realization of the pure scalar state, that the mixing angle can be measured with the absolute statistical uncertainty of 3.8 mrad, corresponding to the CP parameter $f_{CP} = 1.44 \cdot 10^{-5}$ at 68% CL. Between the ICHEP 2024 conference and this proceedings, this result has been published in [7].

References

[1] R. Fleisher, *CP Violation in B Decays: Recent Developments and Future Perspectives*, [hep-ph/ 2402.00710v1]

[2] *2020 Update of the European strategy for particle physics*, CERN-ESU-015-2020.

[3] A. V. Gritsan et al., *Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments*, [hep-ph/2205.07715v2]

[4] M. Pepe, *Review of NA48 CP violation measurements with neutral and charged kaons*, in proceedings of *2009 KAON International Conference* PoS(KAON09)004.

[5] H. Abramowicz et al., Higgs physics at the CLIC electron-positron linear collider, Eur. Phys. J. C 77, 475 (2017).

[6] A. Arishev et al., *The International Linear Collider: Report to Snowmass 2021*, DESY-22-045, [hep-ph/2203.07622v3]

[7] N. Vukasinovic, I. Bozovic Jelisavcic et al., *Probing CPV mixing in the Higgs sector in vector boson fusion at a 1 TeV ILC*, PHYSICAL REVIEW D 110, 032011 (2024).

[8] W. Kilian, et al., *WHIZARD: Simulating multi-particle processes at LHC and ILC*, Eur. Phys. J. C 71, 1742 (2011).

[9] P. Artoisenet et al., *A framework for Higgs characterization*, J. High Energy Phys. 11 (2013) 043.

[10] J. de Favereau et al., *DELPHES 3: A modular framework for fast simulation of a generic collider experiment*, J. High Energy Phys. 02 (2014) 057.

[11] S. Agostinelli et al., *GEANT4—A simulation toolkit*, Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).

[12] P. Mora de Freitas et al., *Mokka/GEANT4: Present and future, International Workshop on Linear Colliders* , LC-TOOL-2003-010.