ILD-PHYS–2024-NNN
03 October 2024

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

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With the current precision of measurements by the ATLAS and CMS experiments, it cannot be excluded that a SM-like Higgs boson is a CP violating mixture of CP-even and CP-odd states. We explore this possibility here, assuming Higgs boson production in ZZ-fusion, at 1 TeV ILC, with unpolarized beams. The full simulation of SM background and fast simulation of the signal is performed, simulating 8 ab^{-1} of data collected with the ILD detector. We demonstrate that the CP mixing angle Ψ_{CP} between scalar and pseudoscalar states can be measured with the statistical uncertainty of 3.8 mrad at 68% CL, corresponding to 1.44 $\cdot 10^{-5}$ for the CP parameter f_{CP}, for the pure scalar state. This is the first result on sensitivity of an e^+e^- collider to measure f_{CP} in the Higgs production vertex in vector boson fusion.

This work was carried out in the framework of the ILD Concept Group

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1 Introduction

Exploring the possibility that CP is violated in Higgs interactions with bosons and fermions is an important part of the physics program both at ongoing experiments and future Higgs factories. The CPV effect is typically weaker in Higgs interactions with vector bosons (HVV) in comparison to those with fermions (Hff) and sensitivity targets to measure CPV effects in these interactions are thus different. A common framework [1] for interpretation of the CPV measurements in bosonic HVV and fermionic Hff vertices at different future experiments is based on the CPV parameter $f_{\rm CP}$ that quantifies the CP-odd contribution to a Higgs interaction. The theoretical target for future colliders to measure $f_{\rm CP}$ is set to 10^{-2} (10^{-6}) in Hff (HVV) vertices.

This analysis [2] brings the first result obtained for the Higgs production in vector boson fusion (VBF), specifically in ZZ-fusion $e^-e^+ \to He^-e^+$, assuming 8 ab^{-1} of data collected with the ILC operating at 1 TeV centre-of-mass-energy with unpolarised beams. The interplay between the production cross section and centrality of signal events makes 1 TeV an optimal energy for CPV measurements in the HZZ vertex in VBF at an e^-e^+ collider.

In this analysis we consider exclusive Higgs decay to $b\bar{b}$ that enables us to avoid the high cross section $e^-e^+ \to e^-e^+\gamma$ background that would otherwise be present in an inclusive analysis. Signal events are generated in Whizard 2.8.3 [3], using the Higgs characterization model [4] within the UFO framework. In this model the parametrization of CP mixing is entirely realized in terms of the mixing angle between scalar and pseudoscalar states, allowing for a completely general description of CP-mixed state [4]. Further interactions of signal with the detector are simulated assuming a generic detector for ILC with the fast simulation DELPHES 3.4.2 (ILCgen cards) [5]. Standard Model background is fully simulated and reconstructed with the ILD detector [6]. The event selection is based on identification of exactly one isolated electron and one isolated positron per event while the remaining Particle Flow Objects (PFOs) are clustered into two jets by the Durham algorithm [7]. For signal events, electrons are isolated by DELPHES isolation processor, while for fully simulated events Marlin *IsolatedLeptonFinder* processor [8] is applied. A multivariate analysis (MVA) [9] is used to further reduce the contribution from several high cross-section background processes, in particular $e^-e^+ \to q\bar{q}e^+e^-$ with the signal-like signature. The signal efficiency is found to be 70%. Around 240 background events expected in 8 ab^{-1} of data are negligible in comparison to 72800 signal events to be selected with the same integrated luminosity.

2 Method of the analysis

We started from the hypothesis that the 125 GeV Higgs mass eigenstate (h) could be a mixture of CP-even (H) and CP-odd (A) states:

$$h = H \cdot \cos\Psi_{\rm CP} + A \cdot \sin\Psi_{\rm CP}, \tag{1}$$

where $\Psi_{\rm CP}$ is the CPV mixing angle. One of the most sensitive observables to nonzero values of $\Psi_{\rm CP}$ is the angle $\Delta\Phi$ between scattering planes. Differently from Hff vertices there is no simple analytical dependence of the sensitive observable $\Delta\Phi$ on the CP mixing angle $\Psi_{\rm CP}$. The dependence is determined empirically by correlating the position of the minimum of $\Delta\Phi$ distribution to the true value of the mixing angle $\Psi_{\rm CP}$ assumed in event generation. As can be seen from Fig. 1(a), the position of the minimum of $\Delta\Phi$ shifts to larger values for positive values of $\Psi_{\rm CP}$ (and similarly to the left for negative values of $\Psi_{\rm CP}$). Reconstructed data has to be corrected for effects of detector acceptance, in order to retrieve the information on the CP state of the Higgs boson in the full physical range of polar angles. The minimum of $\Delta\Phi$ distribution from the reconstructed data can be determined by a local fit with the function $f(\Delta\Phi)$:

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

where A, B, a and b are free parameters. From the principle of the first derivative, the ratio b/a determines the minimum of $\Delta\Phi$ distribution. For $\Psi_{\rm CP}$ values up to 200 mrad, the variable $(b/a)/\Psi_{\rm CP}$ is to a good approximation a linear function of true values of $\Psi_{\rm CP}$, with coefficients k and m determining a slope and a constant term, respectively. Above 200 mrad, the χ^2 fit with $f(\Delta\Phi)$ significantly deteriorates.

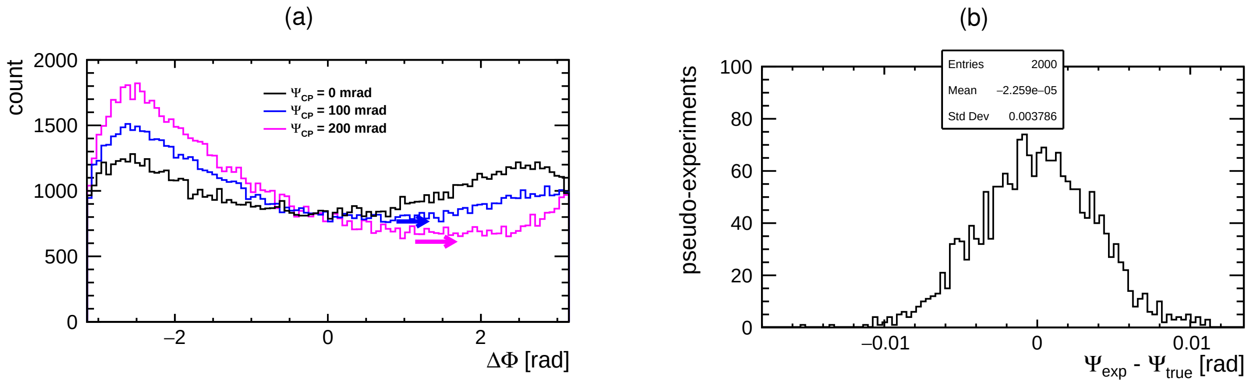

Figure 1: (a) $\Delta\Phi$ distribution for different mixing angles ($\Psi_{\rm CP}$) illustrating the shift of the $\Delta\Phi$ minimum for non-zero values of $\Psi_{\rm CP}$. (b) Statistical dissipation of measured $\Psi_{\rm CP}$ values ($\Psi_{\rm exp}$) w.r.t. the true ones ($\Psi_{\rm true}$).

Knowing the parameters k and m from simulation, $\Psi_{\rm CP}$ values can be determined by solving the quadratic equation:

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

From the fit to a single pseudo-experiment, assuming 8 ab^{-1} of data, one determines $\Psi_{\rm CP}$ = (2.4 $\pm$ 4.0) mrad by solving Eq. (3). In order to estimate the statistical dispersion of results of repeated $\Psi_{\rm CP}$ measurements, we performed 2000 pseudo-experiments each with 8 ab^{-1} of data. The dispersion of the results assuming a pure scalar state is found to be 3.8 mrad at 68% CL, as illustrated in Fig. 1(b). Dispersion of errors (RMS) from repeated pseudoexperiments is 0.4 mrad. Allowing parameters k and m [from Eq. (3)] to vary within their uncertainties, we have estimated a systematic uncertainty from modeling to be significantly less than 1 mrad.

To interpret the obtained precision of measurement of the mixing angle in terms of sensitivity to the CP-odd amplitude $f_{\rm CP}$, we assume that $f_{\rm CP}$ will vary from zero as $\sin^2(\Delta(\Psi_{\rm CP}))$ for the pure scalar state [1], where $\Delta(\Psi_{\rm CP})$ is the absolute statistical uncertainty of the $\Psi_{\rm CP}$ measurement. The statistical uncertainty of 3.8 mrad of the $\Psi_{\rm CP}$ measurement translates into $f_{\rm CP}$ sensitivity of 1.44 $\cdot 10^{-5}$ at 68% CL reaching the theoretical target estimated in [1].

3 References

[1] A. V. Gritsan et al., *Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments* (2022), arXiv: 2205.07715v3 [hep-ex].

[2] N. Vukašinović et al., *Probing CPV mixing in the Higgs sector in vector boson fusion at a 1 TeV ILC*, Phys. Rev. D **110** (3 2024) 032011, DOI: 10.1103/PhysRevD.110.032011.

[3] W. Kilian, T. Ohl, J. Reuter, *WHIZARD-simulating multi-particle processes at LHC and ILC*, The European Physical Journal C **71** (2011), DOI: 10.1140/epjc/s10052-011-1742-y.

[4] P. Artoisenet et al., *A framework for Higgs characterisation*, Journal of High Energy Physics **2013** (2013), DOI: 10.1007/jhep11(2013)043.

[5] J. de Favereau et al., *DELPHES 3: a modular framework for fast simulation of a generic collider experiment*, Journal of High Energy Physics **2014** (2014), DOI: 10.1007/jhep02(2014)057.

[6] ILD Collaboration, *International Large Detector: Interim Design Report* (2020), arXiv: 2003.01116 [physics.ins-det].

[7] S. Catani et al., *New clustering algorithm for multi - jet cross-sections in e+ e- annihilation*, Phys. Lett. B **269** (1991) 432, DOI: 10.1016/0370-2693(91)90196-W.

[8] F. Gaede, J. Engels, *Marlin et al - A Software Framework for ILC detector R&D* (2007), URL: http://www.eudet.org/e26/e27/e584/eudet-report-2007-11.pdf.

[9] A. Höecker et al., *TMVA - Toolkit for Multivariate Data Analysis* (2009), arXiv: 0703039 [physics.data-an].