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

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Although the studies of tensor structure of the Higgs boson interactions with vector bosons and fermions at CMS and ATLAS experiments have established that the $J^{PC}$ quantum numbers of the Higgs boson should be $0^{++}$, small CP violation in the Higgs sector (i.e. ≤ 10% contribution of the CP-odd state) cannot be excluded with the current experimental precision. We review a possibility to measure the CP violating mixing angle between scalar and pseudoscalar states of the extended Higgs sector, at 1 TeV ILC with the ILD detector.

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## 1. Introduction

The violation of CP symmetry is one of Sakharov's conditions to explain baryon asymmetry of the observable Universe. Experimentally observed CP violation (CPV) in systems of flavored mesons is consistent with the CKM transitions of the Standard Model (SM) [1]. Discovery of the Higgs boson, a unique fundamental scalar related to several open questions of the SM, makes it plausible to explore the Higgs sector for signs of CP violation in Higgs interactions with bosons or fermions.

Future Higgs factories, foreseen to operate as $e^+e^-$ colliders, are particularly suitable for this task due to numerous Higgs production and decay processes available over the span of center-of-mass energies ranging from 240-350 GeV at circular colliders (CEPC, FCCee), while linear colliders (ILC, CLIC) are capable to operate at a TeV scale. With rising cross-sections with the center-of-mass energy (Fig. 1 [2]), vector boson fusion (VBF) becomes the dominant mechanism of Higgs production at higher center-of-mass energies, enabling CPV measurements in HVV vertices (V=Z, W). The International Linear Collider (ILC) operating at 1 TeV center-of-mass energy offers a possibility to measure CPV in ZZ-fusion, due to optimal interplay between centrality of this t-channel process and the cross-section dependence on the center-of-mass energy.

The measurement presented here is the first estimate in VBF production channel [3] at a future $e^+e^-$ collider. It assumes 8 $ab^{-1}$ of ILC data simulated with the ILD detector [4] with unpolarized beams. The method is based on CP sensitive angular observable thus complementing the SM Effective Field Theory (SMEFT) measurements in Higgsstrahlung as the standard candle at future Higgs factories running at 240 GeV.

## 2. CPV sensitive observable

The measurement is based on a generic assumption that the 125 GeV Higgs mass eigenstate *h* could be a CPV mixture of CP-even (H) and CP-odd (A) eigenstates of the extended Higgs sector, via some mixing angle $\Psi_{CP}$:

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

The most of the CP related information of the Higgs state is carried by the difference in azimuthal angle $\Delta\Phi$ [5], between the production planes (Fig. 2, Eq. 2), assuming that the Z boson emitted by electron defines the direction of the z-axis in the Higgs rest frame. The angle $\Delta\Phi$ can be retrieved as the angle between vectors $\mathbf{n_1}$ and $\mathbf{n_2}$ orthogonal to electron and positron planes, respectively:

$$\Delta\Phi = \begin{cases} arccos(cos(\Delta\Phi)), \mathrm{sgn}(sin(\Delta\Phi)) \geq 0 \\ 2\pi - arccos(cos(\Delta\Phi)), \mathrm{sgn}(sin(\Delta\Phi)) \leq 0 \end{cases} \quad (2)$$

where:

$$cos(\Delta\Phi) = \vec{n}_1 \cdot \vec{n}_2, \quad \mathrm{sgn}(sin(\Delta\Phi)) = \frac{\vec{q}_1 \cdot (\vec{n}_1 \times \vec{n}_2)}{|\vec{q}_1 \cdot (\vec{n}_1 \times \vec{n}_2)|} \quad (3)$$

and:

$$\vec{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \quad \text{and} \quad \vec{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}\,. \quad (4)$$

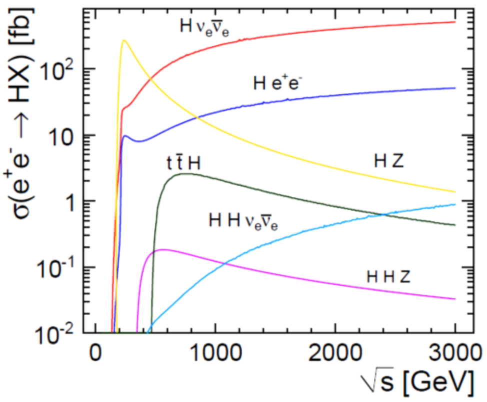


Figure 1. Higgs production cross-sections as a function of the center-of-mass energy.

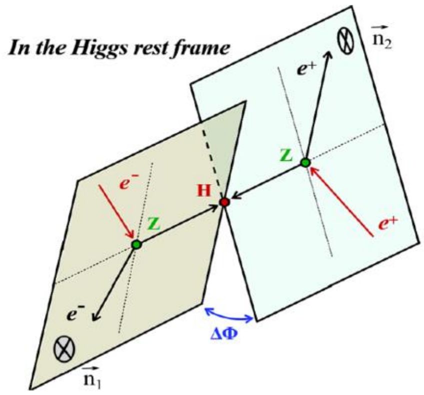


Figure 2. Illustration of CP sensitive observable ΔΦ.

## 3. Event samples and selection

Exclusive decays of the Higgs boson to two b-jets are considered, to avoid high cross-section backgrounds like $e^+e^- \to e^+e^-\gamma$ relevant in the inclusive measurement. We have generated approximately $2{\cdot}10^5$ events, corresponding to twice the nominal integrated luminosity of 8 $ab^{-1}$. Background is fully suppressed with conventional cut-off based selection, without a need to employ multivariate analysis.

### 3. 1 Event samples

Signal events are generated with the Higgs characterization model in the UFO framework of WHIZARD V2.8.3 multiparticle event generator [6]. Background events are simulated as the Standard Model processes in WHIZARD V1.9.5. Detector response is simulated with DELPHES V3.4.2 [7] fast simulation of the ILD detector for ILC.

| 1 TeV | σ (fb) | Expected in 8 $ab^{-1}$ | Reconstructed with ILD |
|---|---|---|---|
| SIGNAL: $\boldsymbol{e^+e^- \to Hee, H \to b\bar{b}}$ | 13 | 104000 | 200000 DELPHES |
| $e^+e^- \to q\bar{q}l^+l^-$ | 255 | $2{\cdot}10^6$ | 5886 |
| $e^+e^- \to q\bar{q}$ | 9375 | $75{\cdot}10^6$ | 120343 |
| $e^+e^- \to q\bar{q}l\nu$ | 4116 | $32.9{\cdot}10^6$ | 955058 |

Table 1. Signal and background processes with cross-sections, number of reconstructed events and number of expected events in 8$ab^{-1}$ of data. Smaller fraction of signal events (~3500 events) are fully simulated.

Corresponding DELPHES card ILCgen should equally well describe performance of the SiD detector for ILC, however we refer here to the ILD detector, since a fraction of signal and background events is fully reconstructed with the ILD detector. Table 1 lists considered processes of signal and background.

### 3.2 Event selection

Background is primarily suppressed by electron isolation in the tracking region, suppressing processes without exactly one isolated electron and one positron per event. DELPHES isolation is applied requiring that the sum of the transverse momenta of particles in a cone (R=0.5) around the isolated electron candidate is not larger than 12% of the candidate's transverse momentum. Minimal transverse momentum of all considered particles is set to 0.5 GeV. Events with one isolated electron and one positron are selected with 71% efficiency. In addition to electron isolation, the following selection criteria are applied: di-jet invariant mass is set between 80 GeV and 160 GeV, reconstructed Z masses should be larger than 30 GeV, transverse momentum of the final state $e^+e^-$ system is larger than 15 GeV and the missing transverse momentum is larger than 150 GeV. In addition, to suppress Higgs production in Higgstrahlung, minimal invariant mass of the final state $e^+e^-$ system is set to 200 GeV. Overall selection efficiency of the signal is ~68%. Background is fully suppressed. Fig. 3 illustrates that the selection is unbiased towards the angular observable $\Delta\Phi$.

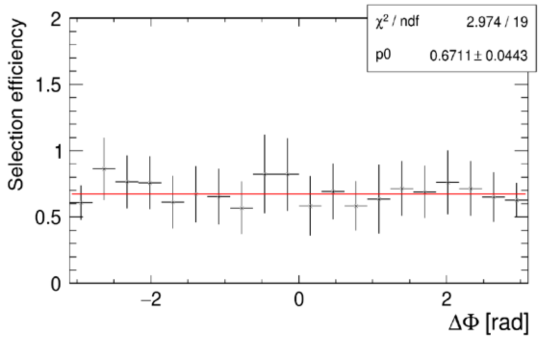


Figure 3. Signal selection efficiency versus angular observable $\Delta\Phi$.

## 4. CPV mixing angle

In order to measure CP violating mixing angle $\Psi_{CP}$, it is necessary to establish a dependence of $\Delta\Phi$ shape to the value of $\Psi_{CP}$. Differently from fermionic vertices (*Hff*) in Higgs decays to a pair of fermions, this dependence can not be derived from the differential cross-section. It has to be determined empirically, what is done here by correlating a position of the local minimum of $\Delta\Phi$ distribution to the value of the mixing angle $\Psi_{CP}$. As can be observed from Fig.4, minima get shifted to the right for non-zero, positive values of $\Psi_{CP}$ (and similarly to the left for negative $\Psi_{CP}$ values).

On the other hand, postion of the local minimum of the angular observable can be extracted from reconstructed experimental data (or pseudo-data in this case). This is illustrated in Fig. 5. The fit around the local minimum is performmed with the function *f*:

$$f(\Delta\Phi)=A+B\cdot \cos(a\cdot\Delta\Phi - b), \tag{5}$$

where *a*, *b*, A and B are free parameters of the fit. The ratio *b/a* corresponds to the function's minimum as can be found with the first derivative test.

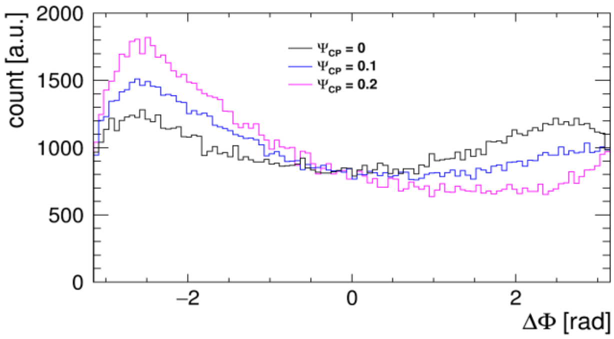


Figure 4. Sensitivity of $\Delta\Phi$ local minima to the mixing angle $\Psi_{CP}$.

Upon determining local minimum *b/a* of $\Delta\Phi$ distribution, one may establish from simulation the dependence of $(b/a)/\Psi_{CP}$ on $\Psi_{CP}$ true value. This dependence is to a good approximation linear ($y=k{\cdot}x+m$), in the $\Psi_{CP}$ range up to 200 mrad. This is illustrated in Fig.6.

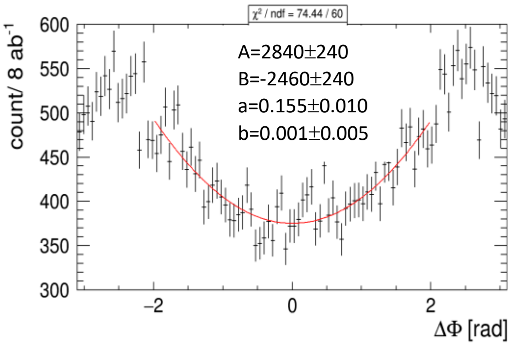


Figure 5. Fit of the local minimum of $\Delta\Phi$ distribution of reconstructed data, with the function *f* from Eq. 5.

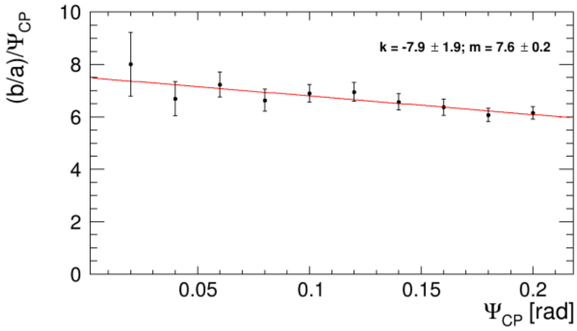


Figure 6. Linear dependence $(k, m)$ of $(b/a)/\Psi_{CP}$ on $\Psi_{CP}$ true value obtained on simulated data.

Knowing the coefficients *k* and *m* of a linear dependence from Fig. 6, $\Psi_{CP}$ can be determined by solving the quartic equation:

$$k\cdot \Psi^2_{CP} + m \cdot\Psi_{CP} - (b/a)=0 \tag{6}$$

For the pure scalar state $\Psi_{CP}=0$, we found $\Psi_{CP} = (2.5 \pm 4.4)$ mrad with $8\text{ab}^{-1}$ of unpolarized ILC data in an individual measurement (pseudo-experiment). In order to estimate statistical dissipation of the expected vaule, we have performed 2000 pseudo experiments, each with 8 $\text{ab}^{-1}$ of data, finding the absolute statistical deviation of $\Psi_{CP}$ of ~ 4 mrad at 68% CL. This is illustrated in Fig. 7.

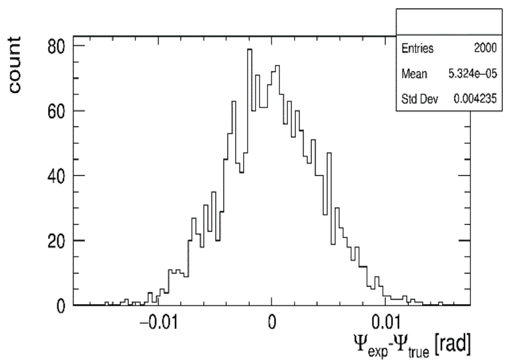


Figure 7. Statistical dissipation of the mean, for the pure scalar state, from 2000 repeated pseudo-experiments.

## 5. Discussion

As discussed in [3], CP violation naturally appears from a sub-set of higher-dimension operators in SMEFT, however measurements based on angular observables provide complementarity without particular assumptions to restrict the parameter space. Common interpretation of different approaches is challenging, and the corresponding framework is proposed in [3] quantifying the CP-odd component via parameter $f_{CP}$. The target of $f_{CP} < 10^{-5}$ for measurements in the HVV vertices comes from the assumptions of up 10% benchmark presence of the CP-odd contribution in the 2HDM model [8], providing sufficient CP violation to explain the baryon asymmetry of the Universe. We have shown that the CP violating mixing angle of the extended Higgs sector can be measured within 4 mrad of absolute statistical uncertainty, for the pure scalar state, at 68% CL. Following formalism from [3], the corresponding sensitivity of $f_{CP}$ is found to be $1.6 \cdot 10^{-5}$ at 68% CL.

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