PROCEEDINGS OF SCIENCE

CP violation in the Higgs sector at ILC

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CP violation is one of the Sakharov's condition for the matter-antimatter asymmetry of the Universe. Experimentally observed size of CP violation is insufficient to account for this. Is CP violated in the Higgs sector? Could the SM-like Higgs boson be a mixture of CP even and CP odd states of an extended Higgs sector? With what precision could such effects be measured at future electron-positron colliders? These questions will be discussed in the light of the latest studies at ILC.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. CP Violation

Experimentally observed size of CP violation (CPV) is not supported by the formalism of the Standard Model (SM). New sources of CPV beyond the (SM) are necessary in order to explain the still open issue of baryon asymmetry of the Universe. CPV in the Higgs sector can be probed in the interaction of Higgs boson with vector bosons or fermions. SM Lagrangian can be modified by adding CP violating terms at a loop level in case of *HVV* vertices or at the Born level in case of *Hff* vertices.

So far, there are only few results on measurement of the CPV mixing angle (Ψ_{CP}) between the Higgs scalar and pseudoscalar states. Among the future projects, ILC has the most promising projection of precision of the Ψ_{CP} measurement, ($\Psi_{\mathrm{CP}} = 4°$), in the fermionic $\mathrm{H} \to \tau^+\tau^-$ decay [1].

2. Probing CP Violation at ILC

There are numerous Higgs production processes available at the International Linear Collider (ILC), like HZ, WW-fusion, ZZ-fusion, at various centre-of-mass-energies, that offers plethora of possibilities for individual measurements and combinations of production and decay channels. Correlation between spin orientations of vector bosons (or fermions) can be extracted from the angle Φ between production or decay planes. Illustration of Φ definition in Higgs production in ZZ-fusion is given in Fig. 1.

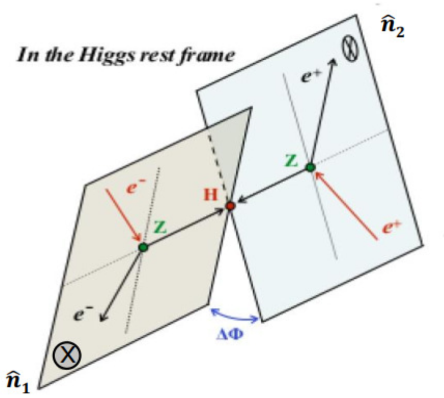

Figure 1: Definition of the CPV sensitive angle Φ in the Higgs boson production in ZZ-fusion.

For the same orientated unit vectors orthogonal to the production planes (as in Fig. 1), CP-sensitive angle between the planes can be defined as:

$$\Phi = a \arccos(\hat{n}_1 \cdot \hat{n}_2) \tag{1}$$

where the unit vectors are:

$$\hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \qquad \text{and} \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|} \tag{2}$$

where $q_{e_i^{-(+)}}, q_{e_f^{-(+)}}$ are momenta of initial and final $e^{\mp}$ states. Coefficient a defines how the second (anti-fermion) plane is rotated w.r.t. the first (fermion) plane and is defined as:

$$a = \frac{q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_{Z_{e^-}} \cdot (\hat{n}_1 \times \hat{n}_2)|} \tag{3}$$

where $q_{Z_{e^-}}$ is momentum of the Z boson in the first plane. Direction of Z boson in the first plane regulates the notion of forward and backward, where if the second plane falls backwards (as illustrated, Fig. 1) a = -1, otherwise a = 1. Similar definitions can be exploited to describe Higgs decays to VV* of $f\bar{f}$, where in case of VV* on-shell boson lies in the first plane.

3. ILC Project

The ILC is a high-luminosity linear e^-e^+ collider with centre-of-mass-energy range of 250-500 GeV (extendable to 1 TeV) aimed for precision studies in the Higgs sector operating as a Higgs factory. The project is also optimised for top-physics and EW studies, as well as to probe new physics phenomena in a direct or indirect way. The electron beam will be polarized to 80%, and the baseline plan includes an undulator-based positron source which will deliver 30% positron polarization. Realization of the ILC as a Higgs factory goes in line with the 2020 Update of the European Particle Physics Strategy [2].

Two detector concepts have been developed, ILD and SiD [3], as general-purpose detectors designed to optimally address the ILC physics goals, operating in a push-pull configuration with the Particle-Flow technique [4] that will play a central role in event reconstruction requiring highly granular calorimeters and excellent low material budget tracking and vertexing systems.

4. CPV Studies at ILC

4.1 CP violation in $H \to \tau^+\tau^-$ at 250 GeV

Higgs fermionic decay to $\tau^+\tau^-$ at 250 GeV centre-of-mass-energy provides excellent sensitivity of the Ψ_{CP} measurement extracted from the shape of Φ in repeated pseudo-experiments. Dependence of the Φ distribution on various assumptions on the CP-mixing strength (Ψ_{CP} value) is illustrated in Fig. 2 (left) [5] . Fig. 2 (right) gives the pull distribution for the generated $\Psi_{\mathrm{CP}} = 0$ mixing angle. The Fig. 2 (right) illustrates the ILC absolute precision to measure Ψ_{CP} to be of order of a hundred of mrad ($\Delta\Psi_{\mathrm{CP}} \sim 4°$), with $e^-_L e^+_R$ polarised samples in the full ILD detector simulation [5]. There is an ongoing analysis in the same channel, at 250 GeV centre-of-mass energy with the SiD detector model [6].

4.2 CP violation in HZZ production at 1 TeV

There is ongoing analysis aiming to estimate achievable precision on Ψ_{CP} (for $\Psi_{\mathrm{CP}} = 0$) from repeated pseudo-experiments reconstructing Φ between the Higgs production planes, where Higgs boson is produced in ZZ-fusion at 1 TeV ILC. Full simulation of ILD detector for ILC is assumed. Fig. 3 (left) illustrates generated information on angle Φ, in the full physical range of polar angles, expected with 1 ab^{-1} of integrated luminosity and ($e^-_L e^+_R$) beam polarization; On Fig. 3 (right),

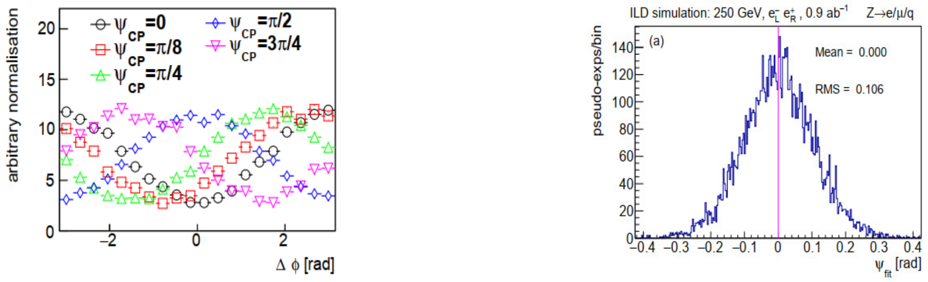

Figure 2: Dependence of the angle Φ on various assumptions on the $\Psi_{\rm CP}$ value (left). Pull distribution for $\Psi_{\rm CP} = 0$, in 0.9 ab^{-1} of fully simulated data with polarised beams at 250 GeV ILC (right).

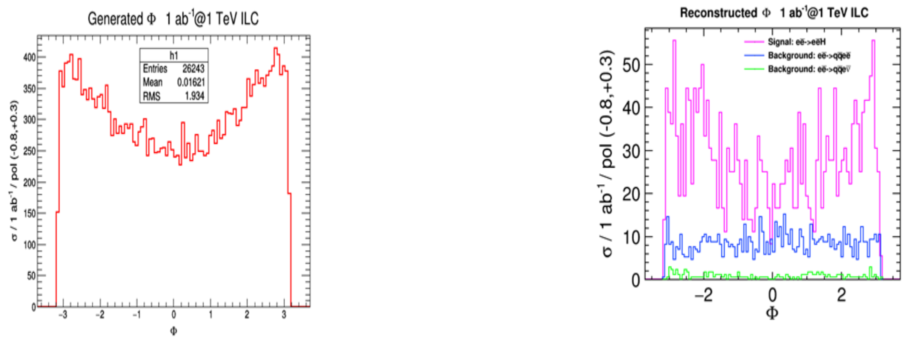

Figure 3: Distribution of the angle Φ at the generator level in the full physical range (left). Reconstructed distributions of Φ in the tracker acceptance region for signal and dominant background processes (right).

reconstructed CP violating observable Φ is given, in the tracker acceptance region, for the exclusive $H \to b\bar{b}$ decay channel, against dominant backgrounds. Events are preselected with $\sim 80\%$ efficiency, to suppress high-cross section background processes, like $e^-e^+ \to qqe\nu$. As expected, background distributions are flat exhibiting no CPV sensitive structure.

References

[1] J. de Blas et al., *Higgs Boson studies at future particle colliders*, *JHEP* **01** (2020) 139.

[2] European Strategy Group, *2020 Update of the European Strategy for Particle Physics*, *CERN-ESU-015* (2020).

[3] T. Behnke et al., *The International Linear Collider Technical Design Report - Volume 4: Detectors*, [arXiv:1306.6329 [physics.ins-det]] (2013).

[4] M. A. Thomson, *Particle Flow Calorimetry and the Pandora PFA Algorithm*, *Nucl. Instrum. Methods* **A 611** (2009), 25 [arXiv:0907.3577 [physics.ins-det]].

[5] 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), 013007.

[6] L. Braun, J. Brau and C. T. Potter, *$H \to \tau^+\tau^-$ CP Violation Analysis for SiD*, LCWS2021, March 2021.