Asymmetry Observables for Probing \( CP \)-Violating Yukawa Interaction of Top-Quark

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The Yukawa coupling between top-quark and Higgs boson not only plays a crucial role in problems related to electroweak vacuum, but also is a promising window for probing the fundamental properties of the Higgs boson(s). Most importantly, indeterminate charge conjugation and parity (\( CP \)) of the Higgs boson can induce \( CP \)-violating Yukawa interactions which are clear hints of new physics. In this paper, we introduce a complete analysis method for searching \( CP \) violation effects in the associated production of top-quark pair and Higgs boson at \( e^{-}e^{+} \) collider. Particularly, two new \( CP \)-odd observables, which are trivial in the rest frame of top-quark pair but sizable in the rest frame of Higgs boson, are predicted. Furthermore, in addition to the advantage that our approach is valid without reconstruction of the top-quarks, we find that the enhancement effect in the rest frame of Higgs boson happens for both \( CP \)-odd and \( CP \)-even observables.

After the long waited era in the elementary particle physics, a scalar particle with mass \( \sim 125 \text{GeV} \) [1] was discovered at LHC in 2012 [2, 3]. However, our knowledge about its physical properties can not be less any more to make a judgment that it is really the Higgs boson who spontaneously breaks the electroweak vacuum and gives masses to the observed vector bosons and fermions, because so far its self-coupling which is responsible for the symmetry breaking has not been measured [4]. On the other hand, theoretical extensions of the Standard Model (SM) always possess more than one Higgs doublet, and hence more scalar particles with either heavier or lighter masses, but having \( CP \) quantum numbers different from the SM prediction, \( J^{CP} = 0^{++} \), are predicted. Therefore, the observed mass eigenstate \( h(125) \) (we will use this notation in the rest of this paper) can be potentially a mixture of the \( CP \) eigenstates. As a natural expectation that the Higgs boson predicted by the SM is at least the dominant component of the observed scalar particle \( h(125) \), decisive measurement on the \( CP \) violation effect, which is a promising potential source of the observed asymmetry between matter and anti-mater in our universe [5, 6], is important and urgent for understanding the physics above electroweak scale. However it is challenging in practice [7].

Without loss of generality, we can assume that \( h(125) \) is a superposition of \( CP \)-even eigenstate \( H \) and \( CP \)-odd eigenstate \( A \),

\[
h = H \cos \xi + A \sin \xi ,
\]

where \( \xi \) is the Higgs mixing angle that has been assumed to be real. The story is further complicated by the couplings of \( H \) and \( A \) to the observed vector bosons and fermions, because what we measure are usually combinations of those couplings and the mixing angle \( \xi \). Therefore, in general, channel by channel studies on the \( CP \) violation effects related to \( h(125) \) is unavoidable.

Soon after \( h(125) \) was observed, its \( CP \) property was studied through \( h \to ZZ \to 4f \) by the ATLAS and CMS collaborations [8–10], and the results disfavor the \( CP \)-odd hypothesis by nearly 3\( \sigma \), which is a rather weak constraint on the mixing angle due to the complexity mentioned above. On the other hand, while \( HVV' \) couplings usually appear at tree level, the \( AVV' \) interactions are only loop induced, and hence \( CP \) violation is heavily suppressed. This drawback absents, theoretically, in the couplings of \( H \) and \( A \) to the fermions, where both types of interaction can happen at tree level and hence are promising probes of \( CP \) violation effects. Recently, the decay of \( h(125) \) to \( \tau^- \tau^+ \) pair channel was analyzed by the ATLAS and CMS collaborations [11, 12], and obviously the bound is again rather weak. The optimization method proposed in Ref. [7] is expected to enhance the sensitivity to a promising level, however, the precision is still limited for inferring physics beyond SM. Many efforts have also been devoted to study possible \( CP \) violation effects in the couplings of \( h(125) \) to top-quark at the LHC [13–20], but the expected sensitivity is not much powerful compared to the constraints from electric dipole moments [21, 22]. It is expected that the sensitivity can be significantly improved at future \( e^{-}e^{+} \) collider [23]. However, since \( h(125) \) are produced (at relatively low energy) through the strahlung process \( e^{-}e^{+} \to hZ \), its \( CP \)-odd component can be completely wash out due to the inherent smallness of the \( A ZZ \) coupling [24]. The \( CP \) quantum numbers can be determined unambiguously at \( \gamma \gamma \) collider [25, 26], but this is not a practical option since it is too remote.

In contrast, the \( CP \)-even and \( CP \)-odd components are generated fairly in the associated production of \( h(125) \) and top-quark pair, \( e^{-}e^{+} \to h t \bar{t} \). On the other hand, many extensions of the SM predict that the heavier the particle the stronger the interactions with unknown sector. The top-quark being the heaviest particle that have been observed, is hence a natural probe of new physics above the electroweak scale [27–30]. Therefore, most likely possible \( CP \) violation effects in the Higgs sector will be demonstrated in first in the interactions between \( h(125) \) and top-quark [13, 23, 24, 31].

The associated production process \( e^{-}e^{+} \to h t \bar{t} \) is dom-
inantly generated by radiation of the Higgs boson from one of the top-quarks. Contribution of the production in association with a $Z$ boson, $e^-e^+ \rightarrow hZ \rightarrow h\ell\ell$, is very small, only a few percent when $\sqrt{s} \leq 1$TeV [32]. Meanwhile, the photon exchange channel contributes the bulk of the cross section. It has been show that the total cross section and the top-quark polarization would be good observables for measuring $CP$ violation parameter [24]. On the other hand, since the top-quark decays before hadronization, its spin-polarization can be measured by studying the polar angle [33] as well as the azimuthal angle distributions [34] of its decay products, particularly the lepton. Furthermore, the associated spin correlations between the top-quark and anti-top-quark provide much more richer physics for probing anomalous interactions in the production dynamics [35]. However, previously works studied either $CP$-even observables [24, 36] which is insensitive to the $CP$ violation parameter, or $CP$-odd observables which requiring reconstruction of the momenta of top-quark and anti-top-quark [13, 23, 24, 31, 37].

Recently, a general method for analyzing possible non-trivial spin correlations by using angular correlations between leptons emerging from the top-quark pair decay was proposed [38]. Based on these distributions, a complete set of asymmetry observables is constructed for investigating new physics in the production dynamics. It has been shown that, the angular distributions of the leptons from top-quark and anti-top-quark decays are insensitive to new physics in the decay side [39], and furthermore non-trivial dependence of the energy distributions are completely removed in the asymmetry observables due to its definition. In consideration of these advantages, in this paper we propose a complete set of asymmetry observables to study the $CP$ violation effects in the process $e^-e^+ \rightarrow h\ell\ell$.

For our discussion, we assume that Yukawa interactions between the $CP$-even eigenstate $H$ and the $CP$-odd eigenstate $A$ and the top quark are conserving, such that the Higgs mixing parameter $\xi$ in Eq. (1) is the only source of $CP$ violation in the Higgs sector. In this case, the corresponding Lagrangian can be parameterized as,

$$\mathcal{L}_{\text{int}} = -g_{H\ell\ell} \bar{\psi}_\ell \gamma^5 \psi_\ell H - ig_{A\ell\ell} \bar{\psi}_\ell \gamma^5 \psi_\ell A.$$  \hspace{1cm} (2)

For the associated production process $e^-e^+ \rightarrow h\ell\ell$, production rates of the $CP$-even and $CP$-odd components in the mass eigenstate $h(125)$ are subjected to the above Lagrangian and the mixing parameter $\xi$. Since $h(125)$ will be looked into inclusively, we don’t need to consider the projection effect [24] in its decay (in practice, usually we can not investigate all decay channels, in this case projection effect has to be taken into account for precision measurement). Therefore, the interactions between the mass eigenstate $h(125)$ and the top-quark can be described as,

$$\mathcal{L}_{\text{int}} = -g_{H\ell\ell} h(\cos \xi \bar{\psi}_\ell \gamma^5 \psi_\ell + i\kappa_{H\ell\ell} \sin \xi \bar{\psi}_\ell \gamma^5 \psi_\ell),$$ \hspace{1cm} (3)

where $\kappa_{H\ell\ell} = g_{A\ell\ell}/g_{H\ell\ell}$. In general $\kappa_{H\ell\ell}$ can be arbitrary in both its magnitude and sign, and hence model-dependent. The strength of $CP$ violation effect is also affected by kinematic factors. For instance, the $CP$ violating phase measured through the observables proposed in Ref. [32] is suppressed by a factor of $\sim 0.2$. In this paper, a model-independent assumption $\kappa_{H\ell\ell} = 1$ will be continuously-used unless it is mentioned. Furthermore, we will take $g_{H\ell\ell}$ as the Yukawa coupling of top-quark in the SM.

We will study the spin correlation effects in the leptonic decays of top-quarks. For the process $e^-e^+ \rightarrow h\ell\ell$, the differential cross section can be written as [38],

$$\frac{d\sigma}{d \cos \theta_1 d \phi_1 d \cos \theta_2 d \phi_2} = \sum_{\lambda_f, \lambda_f'} D_{\lambda_f'}^{\lambda_f}(\theta_1, \phi_1),$$  \hspace{1cm} (4)

where $\theta_i$ and $\phi_i$ with $i = 1$ ($i = 2$) are the polar angle and azimuthal angle of anti-lepton (lepton) in a chosen reference frame $R$; $\lambda_f = s, 0, \pm 1$ are the helicity of the lepton-pair system projected along the $z$-axis of the reference frame $R$; $P_{\lambda_f}$ and $D_{\lambda_f}^{\lambda_f}(\theta_1, \phi_1)$ stand for the spin-projected production density matrix and the correlations functions of the leptonic pair system. Within the SM, the correlation function $D_{\lambda_f}^{\lambda_f}(\theta_1, \phi_1)$ is universal for any production dynamics, and has been given in Ref. [38]. On the other hand, the spin-projected production helicity amplitudes can be generally written as

$$\mathcal{M}_P(\lambda, \lambda_f) = \sum_{\lambda_f} \mathcal{G}^{\mu\nu}(\lambda_f) \mathcal{L}_\mu(\lambda) \epsilon_\nu(\lambda_f),$$ \hspace{1cm} (5)

where $\mathcal{L}_\mu(\lambda)$ is current of the initial electron pair, and $\lambda$ stands for its polarization (since beam polarization effect is also sensitive to the $CP$ violation parameter, or $CP$-odd observables which requiring reconstruction of the momenta of top-quark and anti-top-quark [13, 23, 24, 31, 37]. Apart from the total cross section, which can be good observable before one reaches the chiral limit at very high energies, 15 additional asymmetry observables can be defined based on the correlation function $D_{\lambda_f}^{\lambda_f}(\theta_1, \phi_1)$. The magnitudes of these asymmetry observables are determined by the spin-projected density matrix $P_{\lambda_f}$, the analytical results are too lengthy and will be given elsewhere [41]. In terms of the number of events in corresponding phase space regions, the asymmetry observables can defined as follows,

$$C_{\phi_1} = \frac{N(\sin \phi_1 > 0) - N(\sin \phi_1 < 0)}{N(\sin \phi_1 > 0) + N(\sin \phi_1 < 0)},$$ \hspace{1cm} (6a)

$$C_{\phi_2} = \frac{N(\sin 2\phi_2 > 0) - N(\sin 2\phi_2 < 0)}{N(\sin 2\phi_2 > 0) + N(\sin 2\phi_2 < 0)};$$ \hspace{1cm} (6b)

$$C_{\phi_1 \phi_2} = \frac{N(\cos \theta_1 \sin \phi_1 \phi_2 > 0) - N(\cos \theta_1 \sin \phi_1 \phi_2 < 0)}{N(\cos \theta_1 \sin \phi_1 \phi_2 > 0) + N(\cos \theta_1 \sin \phi_1 \phi_2 < 0)}.$$  \hspace{1cm} (6c)
Most importantly, the asymmetry observables listed above are valid in any reference frame [38]. Because it is the left-handed current through which top-quark and anti-top-quark decay, the spin-projected production density matrix elements and hence the asymmetry observables have relatively strong dependence on the reference frame. Therefore, performing optimization for finding most sensitive asymmetry observables in various reference frames, which is also one of the advantages of our approach, is important. In this paper, we consider two reference frames that can be determined directly without of reconstructions of top-quarks: 1) the rest frame of the top-quark pair system, denoted by \( R_\psi \); 2) the rest frame of the Higgs boson, denoted by \( R_h \). Definitions of the axes of these two reference frames are given in the caption of Fig. 1.

\[
A_{\theta_1, \theta_2} = \frac{N(\cos \theta_1 \cos \theta_2 > 0) - N(\cos \theta_1 \cos \theta_2 < 0)}{N(\cos \theta_1 \cos \theta_2 > 0) + N(\cos \theta_1 \cos \theta_2 < 0)},
\]

\[
A_{\phi, \phi'} = \frac{N(\cos \theta_1 \cos \phi_1' > 0) - N(\cos \theta_1 \cos \phi_1' < 0)}{N(\cos \theta_1 \cos \phi_1' > 0) + N(\cos \theta_1 \cos \phi_1' < 0)},
\]

where \( \phi_\pm = (\phi_1 \pm \phi_2)/2 \). The first three equations give 6 CP-odd observables, and the last five equations give 9 CP-even observables.

![Fig. 1. Dominant geometry configurations of the momenta and helicity of the top-quark pair in the rest frames of (a) the top-quark pair and (b) the scalar particle \( h(125) \). The \( z \) axis of \( R_\psi \) is along the flying direction of the top-quark pair system, and the \( x \) axis is determined by the plane spanned by the momentum of \( e^- \) and the \( z \) axis. The \( z \) axis of \( R_h \) is along the flying direction of \( h(125) \), and the \( x \) axis is determined by the plane spanned by the momentum of \( e^- \) and \( h e z \) axis.](image)

![Fig. 2. Dependence of the CP-even asymmetry observables on the CP violation parameter for \( \sqrt{s} = 500 \text{GeV} \). For illustration, \( 10^5 \) events are generated by using MadGraph [42].](image)

Fig. 2(a), 2(b) and 2(c) show the dependences of the above 6 CP-odd asymmetry observables \( C_{\phi_1}, C_{\phi_2} \) and
\(C_{\theta, \phi, \psi}\) strongly depend on the boost due to that they are related to the polar angle. This can been clearly seen in Fig. 2(c): in the reference frame \(R_{h}\), \(C_{\theta, \phi, \psi}\) are sensitive to the \(CP\) violation parameter \(\xi\), but they are trivial in the reference frame \(R_{\psi}\).

\[
\begin{align*}
\text{(a)} & \quad \text{(b)} & \quad \text{(c)} & \quad \text{(d)} & \quad \text{(e)} \\
& & & & \\
\end{align*}
\]

**FIG. 3.** Dependence of the \(CP\)-even asymmetry observables on the \(CP\) violation parameter for \(\sqrt{s} = 500\text{GeV} \).
ities of the top-quark pair system (Higgs boson) in the laboratory frame, respectively. Their ratio can be easily calculated,
\[ \frac{\gamma_h \beta_h}{\gamma_\psi \beta_\psi} = \frac{m_\psi}{m_h} \gtrsim 2.77, \]
where \( m_\psi \) is the invariant mass of the top-quark pair, and the approximation stands for \( m_\psi < 2m_t \) due to bound state effect near the threshold. Similarly, there is also an enhancement in the longitudinal component (\( \lambda_f = 0 \)), even through the scale factor is relatively small (the ratio is \( \gamma_h/\gamma_\psi \approx 1.2 \) at the threshold).

The enhancement effect does not only happen in the CP-odd observables, the CP-even observables are also strongly affected by the boost transformation. Fig. 3(a)-3(e) show the \( \xi \) dependences of the above 9 CP-even asymmetry observables. The enhancement effect can be clearly seen in Fig. 3(a), 3(c) and 3(e) which correspond to distributions of the observables \( A_{\theta_1}, A_{\theta_2}, A_{\theta_1 \theta_2} \), respectively.

In summary, we have proposed a complete analysis method for probing possible CP-violation effects in the Yukawa interaction of top-quark at \( e^-e^+ \) collider. Our approach is valid without reconstruction of the top-quarks, and hence the experimental sensitivity can be improved. In addition, we have demonstrated that for both CP-odd and CP-even observables, there is an enhancement effect in the rest frame of Higgs boson. This is important for investigating the CP-violation effect at future \( e^-e^+ \) collider.

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