Probing the CP structure of the top quark Yukawa coupling: Loop sensitivity versus on-shell sensitivity

Till Martini^{1,*} Ren-Qi Pan,^{2,†} Markus Schulze,^{1,‡} and Meng Xiao^{2,§}

¹*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, 12489 Berlin, Germany*

²*Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China*

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The question whether the Higgs boson is connected to additional CP violation is one of the driving forces behind precision studies at the Large Hadron Collider. In this work, we investigate the CP structure of the top quark Yukawa interaction—one of the most prominent places for searching for New Physics—through Higgs boson loops in top quark pair production. We calculate the electroweak corrections including arbitrary CP mixtures at next-to-leading-order in the Standard Model Effective Field Theory. This approach of probing Higgs boson degrees of freedom relies on the large $t\bar{t}$ cross section and the excellent perturbative control. In addition, we consider all direct probes with on-shell Higgs boson production in association with a single top quark or top quark pair. This allows us to contrast loop sensitivity versus on-shell sensitivity in these fundamentally different process dynamics. We find that loop sensitivity in $t\bar{t}$ production and on-shell sensitivity in $t\bar{t}H$ and tH provide complementary handles over a wide range of parameter space.

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I. INTRODUCTION

The discovery of the Higgs boson by the ATLAS and CMS Collaborations [1–3] in 2012 has sparked an extensive research effort to precisely measure its properties and origin. In fact, it has become one of the main goals of collider phenomenology. Data shows that the discovered particle is consistent with the spin-zero Higgs boson of the Standard Model (SM) [4,5]—within the current uncertainties. One defining property is the CP -even *Yukawa interaction* between the Higgs boson and the SM fermions, which is proportional to the fermion mass. CP -violating contributions are in principle allowed by gauge as well as space-time symmetries, and they are theoretically compelling in the context of the baryon asymmetry in the universe. In fact, many generic extensions of the SM, such as two-Higgs-doublet models [6–10] or composite Higgs models [11–25], contain modifications of the simple CP structure of the SM. It is therefore of highest importance to search for

CP -odd contributions that modify the SM interactions. In this regard, the top quark Yukawa interaction stands out due to the large top quark mass, which implies a large coupling. Moreover, top quarks are copiously produced at the LHC, which makes them ideal for searching for New Physics. For example, the CMS and ATLAS experiments [26,27] recently presented first measurements which resulted in the exclusion of a pure CP -odd coupling at more than 3σ , still leaving large room for mixtures of CP -even and CP -odd components.

In this work, we propose a novel way to probe the CP properties of the top quark Yukawa coupling: We want to challenge the SM at loop level, where the Higgs boson only appears through off-shell degrees of freedom. Hence, we study top quark pair production accounting for electroweak corrections. The leading effects are the $\mathcal{O}(\alpha)$ weak corrections to the QCD-induced $pp \rightarrow t\bar{t}$ process, which we calculate for CP -even and CP -odd Htt couplings allowing arbitrary mixtures. Our strategy is motivated by the abundant data of top quark pairs produced at the LHC and excellent perturbative control over the theoretical predictions. In fact, the LHC will have produced almost 500 million top quarks by 2023, while already today, theoretical predictions reach an accuracy of only a few percent [28–33]. These prospects are only getting brighter with the high-luminosity runs commencing in 2027 and high ambitions of the theory community towards next-to-next-to-next-to-leading order (N^3LO) calculations [34–36]. Another promising feature is that this approach, using $t\bar{t}$, is

*till.martini@physik.hu-berlin.de

†renqi.pan@cern.ch

‡markus.schulze@physik.hu-berlin.de

§meng.xiao@cern.ch

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free from *penalties* of Higgs boson branching fractions and ambiguities of a complicated final state, which is in contrast to on-shell Higgs production processes such as $pp \rightarrow t\bar{t}H$. Yet, it is at the same order in the perturbative counting.

We note that this idea was actually presented for the first time a long time ago in Ref. [37] proposing the difference in the transverse energy distribution of leptons and antileptons from $t\bar{t}$ events at hadron colliders as probe of CP violation in the Higgs sector. A previous study [38] has also already touched upon this idea. The authors consider $t\bar{t}$ production at the LHC and allow rescaling the CP -even Yukawa coupling in a pre-existing SM calculation. An actual measurement by CMS [39] shows very promising sensitivity that warrants further investigation. In contrast, our work requires calculating the respective Higgs boson loops from scratch due to the new CP -odd components. We present a realistic phenomenological analysis for the most general CP -even and CP -odd coupling structure, for the first time, and estimate the sensitivity using the same observables as in the CMS analysis in Ref. [39]. In addition, we simulate the competing on-shell processes $pp \rightarrow t\bar{t}H$, $pp \rightarrow tqH$, and $pp \rightarrow tWH$ with the same CP -even and CP -odd top quark Yukawa couplings in order to have a fair comparison and to capture dominant backgrounds. We partly resort to our previous work in Ref. [40] and extend it by the calculation of the $pp \rightarrow tWH$ process, which we discuss in more detail. As a result, all on-shell processes are publicly available¹ in the JHUGen Monte-Carlo generator [40–44], which is heavily used in experimental analysis [4,26,45–48]. We also provide a publicly available² extension of MCFM [49,50], which yields the loop correction to $t\bar{t}$ production. Finally, we note that our implementation also allows for the most general CP -even and CP -odd HWW anomalous couplings in the tWH process. For the purpose of this work, however, we keep them at their SM value. Recently, the combination of all on-shell processes has also been studied in Ref. [51]. Relevant works on a subset of these processes can be found in Refs. [52–62]. Also low-energy measurements of the electric dipole moment yield complementary constraints on the CP -odd components, which are remarkably strong [63–67] and need to be considered in real data analyses.

II. LOOP SENSITIVITY TO THE CP STRUCTURE OF THE TOP-HIGGS COUPLING

A. The next-to-leading order (NLO) electroweak effects

The dependence of the $t\bar{t}$ production cross section on the top quark Yukawa coupling arises only when considering electroweak loop corrections. For the SM hypothesis, theoretical predictions for top quark pair production

including electroweak corrections have been known for a long time [38,68–72] and their implementation is available via published codes like MCFM [49]. Version 2.1 of HATHOR [73] allows for the calculation of electroweak corrections to top quark pair production with a scalable CP -even top quark Yukawa coupling.

In Ref. [74] the calculation of electroweak loops in hadronic $t\bar{t}$ production with modified couplings of the top quark to the electroweak gauge bosons in terms of higher-dimensional EFT operators has been presented by some of us. Building upon the techniques developed in Ref. [74], we allow for arbitrary CP scenarios of the top quark Yukawa couplings parametrized by the effective Lagrangian of the interaction of the top quark t and a scalar particle H

$$\mathcal{L}(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\kappa + i\tilde{\kappa}\gamma_5) \psi_t H, \quad (1)$$

where the κ term is CP even, and the $\tilde{\kappa}$ term is CP odd. The parameters κ and $\tilde{\kappa}$ can be connected to the real and imaginary part of the Wilson coefficient $C_{tt}^{u\varphi}$ of the respective dimension-six operator $Q_{u\varphi}$, as defined in the Warsaw basis of the Standard Model Effective Field Theory (SMEFT) [75], by

$$\begin{aligned} \kappa &= 1 - \frac{v}{\sqrt{2}m_t} \frac{v^2}{\Lambda^2} \text{Re}[C_{tt}^{u\varphi}], \\ \tilde{\kappa} &= -\frac{v}{\sqrt{2}m_t} \frac{v^2}{\Lambda^2} \text{Im}[C_{tt}^{u\varphi}]. \end{aligned}$$

This effective Lagrangian incorporates additional CP -odd states, inherent to, e.g., SUSY or two-Higgs-doublet models, while allowing for arbitrary CP mixing with CP -even states, eventually recovering the SM for $\kappa = 1$ and $\tilde{\kappa} = 0$ (cf. Ref. [76]). We employ the Feynman rules implied by the Lagrangian in Eq. (1) to calculate predictions for top quark pair production including electroweak corrections while parametrizing arbitrary CP scenarios of the top quark Yukawa coupling by κ and $\tilde{\kappa}$.

Figure 1 shows sample diagrams for the production of a top quark pair in $q\bar{q}$ annihilation or gluon fusion including a Higgs boson running in the loop. The final state corrections shown in Fig. 1(a) apply to both gluonic and quark-antiquark s -channel production. Due to the scalar and pseudoscalar contributions to the top quark Yukawa coupling in Eq. (1), the interference terms of the tree level with the Higgs-loop diagrams are solely comprised of terms proportional to $(\kappa^2 + \tilde{\kappa}^2)$ or $(\kappa^2 - \tilde{\kappa}^2)$ when neglecting the masses of the light quarks. These terms are infrared finite but contain UV divergences. Thus, the renormalization of the top quark wave function and the top quark mass has to be consistently performed with the modified top quark Yukawa coupling in order to ensure the cancellation of the

¹<https://spin.pha.jhu.edu>.

²https://github.com/TOPAZdevelop/MCFM-8.3_EWSMEFT_ADDON.

FIG. 1. Exemplary weak corrections from Higgs boson exchange to $t\bar{t}$ production: Final-state vertex correction affecting the s -channel both in $q\bar{q}$ annihilation and gluon fusion (a). Box diagram (b), vertex correction (c), and self-energy corrections (d) to the t -channel in gluon fusion.

UV divergences for arbitrary values of κ and $\tilde{\kappa}$. Following Ref. [77], we write the bare top quark field $t_0 = (1 + \frac{1}{2}\delta Z_t)t$ and the bare top quark mass $m_0 = m + \delta m_t$ in terms of the respective renormalized quantities t and m together with the renormalization constants

$$\delta Z_t = -\text{Re}[\Sigma_t^L(m_t^2) + \Sigma_t^R(m_t^2)] - 2m_t^2 \frac{\partial}{\partial p^2} \text{Re}[\Sigma_t^L(p^2) + \Sigma_t^R(p^2) + 2\Sigma_t^S(p^2)]|_{p^2=m_t^2},$$

$$\delta m_t = \frac{m_t}{2} \text{Re}[\Sigma_t^L(m_t^2) + \Sigma_t^R(m_t^2) + 2\Sigma_t^S(m_t^2)].$$

The terms $\Sigma_t^\lambda(p^2)$, ($\lambda = L, R, S$) are the chiral self energies calculated at one-loop order with the electroweak gauge bosons and the Higgs boson running in the loop. In the Higgs sector, they receive modifications with respect to the SM when arbitrary CP scenarios of the top quark Yukawa coupling are taken into account

$$\Sigma_{tH}^L = \Sigma_{tH,SM}^L(\kappa^2 + \tilde{\kappa}^2), \quad (2)$$

$$\Sigma_{tH}^R = \Sigma_{tH,SM}^R(\kappa^2 + \tilde{\kappa}^2), \quad (3)$$

$$\Sigma_{tH}^S = \Sigma_{tH,SM}^S(\kappa^2 - \tilde{\kappa}^2). \quad (4)$$

After renormalization, the one-loop amplitude is UV finite for arbitrary values of κ and $\tilde{\kappa}$ and remains without any dependence on interference terms proportional to $\kappa\tilde{\kappa}$. However, because of different contributions proportional to $(\kappa^2 + \tilde{\kappa}^2)$ as well as $(\kappa^2 - \tilde{\kappa}^2)$, the shapes of kinematic distributions are separately sensitive to κ and $\tilde{\kappa}$.

We build upon the existing implementation of the electroweak corrections to top quark pair production in MCFM [49] and modify the code by the analytic results of the calculation outlined above. This extension is publicly available as an external add-on to the MCFM program. With the modified Monte-Carlo generator MCFM, the relative corrections to the LO result

$$\delta_{\text{wk}} = \frac{d\sigma_{\text{wk}}^{\text{NLO}} - d\sigma^{\text{LO}}}{d\sigma^{\text{LO}}}$$

can be calculated for multidimensional kinematic distributions dependent on κ and $\tilde{\kappa}$. Following Ref. [39], where the size of a pure CP -even top Yukawa coupling was measured through the distributions of the invariant mass of the top quark pair $M_{t\bar{t}}$ and their rapidity difference, $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$, we show the electroweak correction factor for these distributions in Fig. 2. The rapidity difference shows a strong dependence on the CP structure of the top quark Yukawa coupling: The CP -even contribution increases the central region while the CP -odd contribution decreases it. The invariant mass of the top quark pair shows dependence on the CP structure in the threshold region as well as in the tail. Therefore, these kinematic distributions are promising candidates for probing the size of possible CP mixtures.

FIG. 2. The ratio of weak corrections over the LO $t\bar{t}$ production cross section varies with the sensitive kinematic variables $\Delta y_{t\bar{t}}$ (left) and $M_{t\bar{t}}$ (right) on generator level for different anomalous parameters κ and $\tilde{\kappa}$. The black lines correspond to the SM case.

B. Expected sensitivity through top quark pair production

To avoid complicated combinatorial issues, we perform the study in the semileptonic channel, where one top quark decays hadronically and the other decays leptonically. This final state consists of one lepton (electron or muon), missing transverse momentum, four jets from two bottom quarks and two light-flavor quarks. The main background comes from single top, V + jets and QCD multijets processes. For simplicity, we simulate the single top process to extract the shape and rescale it to the expectation of all background processes according to the results presented in the CMS analysis [39].

In this study, the events are simulated by MadGraph5_v2.6.4 [78] and interfaced to Pythia8.1 [79] for parton shower. The detector simulation is implemented by Delphes3 [80] with the CMS detector setting. The NLO weak effects are incorporated in the generated LO events by performing a two-dimensional reweighting. The weights are obtained from the above calculation, as implemented in our publicly available extension of the MCFM program, in the $M_{t\bar{t}} - \Delta y_{t\bar{t}}$ phase space, and applied to the LO events based on their truth level information. The simulated events are normalized to the $t\bar{t}$ production cross section of $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb [32,81,82] predicted at next-to-next-to-leading order (NNLO) QCD accuracy. The cross section of single top quark production is normalized to the NLO QCD prediction [83,84].

Jets and leptons with $p_T > 30$ GeV and $|\eta| < 2.4$ are selected. Events are required to have four jets and exactly one lepton. Two of the four jets should be b -tagged jets. For the W boson that decays leptonically, its transverse mass $M_T(W)$ is required to be less than 140 GeV. $M_T(W)$ is defined as $M_T(W) = \sqrt{2p_T^\ell p_T^{\text{miss}} [1 - \cos(\Delta\phi_{\ell, \vec{p}_T^{\text{miss}})]}$, where p_T^ℓ is the magnitude of the transverse momentum of the

lepton and $\vec{p}_T^{\text{miss}}$ denotes the missing transverse momentum. The other W boson is reconstructed from the two light flavor jets. Top quark pairs are reconstructed through a maximum likelihood method [85].

The ratio of the weak corrections over the LO cross section in the two-dimensional plane of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ at parton level is shown in Fig. 3. The SM couplings ($\kappa = 1$, $\tilde{\kappa} = 0$) are used. The corrections illustrate a correlation pattern between the two variables, thus it is important to perform the analysis in 2D. The number of events in the 2D space after event selection and reconstruction are shown in the right plot of Fig. 3.

Nonzero κ and $\tilde{\kappa}$ values would distort the event distributions as shown in Fig. 3, and the effects would propagate to the reconstructed kinematics. The amount of CP violation of the top quark Yukawa coupling can be quantified by the parameter

$$f_{CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2} \text{sign}\left(\frac{\tilde{\kappa}}{\kappa}\right),$$

which is naturally restricted to values from -1 to 1 . Its absolute value represents the fractional size of the CP -odd component, and its sign reflects the relative phase of the two couplings. We use the reconstructed 2D distribution of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ to extract the value of the CP mixture parameter f_{CP} . A profile likelihood method is used to obtain the expected sensitivity at 300 fb^{-1} and 3000 fb^{-1} , respectively. Theoretical uncertainties of the signal and background processes are taken into account. In particular, QCD uncertainties of the $t\bar{t}$ process at NNLO are about 5% in the most relevant regions of the $\Delta y_{t\bar{t}}$ and $M_{t\bar{t}}$ distributions [32]. Thus, we assign an overall 5% uncertainty to the $t\bar{t}$ rate. The size of the uncertainty is found to have little impact on the results. The details of the results will be discussed in Sec. IV.

FIG. 3. Left: The size of NLO weak correction over LO prediction in the two-dimensional $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ plane, obtained at truth level with $\kappa = 1$ and $\tilde{\kappa} = 0$. Right: Number of simulated events in the two-dimensional plane of $M_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ at reconstruction level.

III. ON-SHELL SENSITIVITY TO THE CP STRUCTURE OF THE TOP-HIGGS COUPLING

A. Higgs production in association with a single top quark

The associated production of a single top quark or a top quark pair with a Higgs boson is dependent on the top quark Yukawa coupling at tree level already. Respective analyses for hadronic $t\bar{t}H$ and tqH production are presented in Ref. [40]. For this work, we complete the existing results by also considering the associated production of a single top quark with a W and a Higgs boson. The tWH production at tree level has two categories of Feynman diagrams as shown in Fig. 4. One category is induced by the Htt coupling and the other is induced by the HWW coupling. These two categories of Feynman diagrams interfere destructively in the SM, which leads to a small total cross section of about 17 fb in the SM. However, CP violation would increase the total cross section especially when the relative sign of the Htt and HWW couplings flips. Single top quark production in association with a Higgs boson is also sensitive to the relative sign of the Htt and HWW couplings due to these interference terms. To consider arbitrary CP scenarios for the top quark Yukawa coupling we use again the Feynman rules implied by the Lagrangian in Eq. (1) to calculate theoretical predictions for the tWH production. We also include anomalous HWW couplings by following the notation of Refs. [41–43] to parametrize the Lagrangian for the interaction of a scalar H and two W bosons

$$\begin{aligned} \mathcal{L}(HWW) = & \frac{M_W^2}{v} \left[g_1^{WW} W_\mu^+ W_\mu^- - \frac{g_2^{WW}}{M_W^2} W_{\mu\nu}^+ W_{\mu\nu}^- \right. \\ & + \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2} (W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{H.c.}) \\ & \left. - \frac{g_4^{WW}}{M_W^2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- \right] H. \end{aligned}$$

Again, the coupling parameters above have direct relations to Wilson coefficients of corresponding dimension-six operators in the Warsaw basis of the SMEFT (cf. Refs. [44,86]). Our results are incorporated in the JHUGen thereby completing the framework's

FIG. 4. Two typical Feynman diagrams of the tWH production at tree level. The Htt induced process (left) interferes with the HWW induced process (right).

implementation of single top quark production in association with a Higgs boson with anomalous Htt and HWW couplings. In this paper, the tWH production includes both the top quark associated process and the antitop quark associated process and the HWW couplings are set to their SM values.

B. Expected sensitivity through Higgs production in association with a single top quark

We estimate the expected constraints on the top-Higgs CP property in the tWH process using a matrix element method. The matrix element likelihood approach (MELA) is designed to extract all essential information from the complex kinematics of a given final state. It can transform complex kinematics into a minimal set of discriminants calculated from the ratios of the matrix elements. To distinguish two different hypotheses, the ratio of probabilities $\mathcal{P}$ for the two hypotheses offers an optimal tool according to the Neyman-Pearson lemma [87]. For measurements of properties of the Higgs boson, two types of discriminants [40,43] defined as below have proven to be useful

$$\mathcal{D}_{\text{alt}} = \frac{\mathcal{P}_A(\vec{\Omega})}{\mathcal{P}_A(\vec{\Omega}) + \mathcal{P}_B(\vec{\Omega})}, \quad (5)$$

$$\mathcal{D}_{\text{int}} = \frac{\mathcal{P}_{\text{int}}(\vec{\Omega})}{\mathcal{P}_A(\vec{\Omega}) + \mathcal{P}_B(\vec{\Omega})}, \quad (6)$$

where $\vec{\Omega}$ represents the 4-momenta of all particles in each final state. The probability densities $\mathcal{P}$ under certain hypotheses A and B ($\mathcal{P}_A(\vec{\Omega})$ and $\mathcal{P}_B(\vec{\Omega})$) for each event are calculated through the squared matrix element. Parton distribution functions have to be taken into account in the calculation when multiple initial parton states are concerned. $\mathcal{D}_{\text{alt}}$ is useful to disentangle hypotheses A and B, while $\mathcal{D}_{\text{int}}$, using the interference probability density $\mathcal{P}_{\text{int}}(\vec{\Omega})$ between two hypotheses, is sensitive to the interference effect.

TABLE I. Cross sections and expected number of events for signal and other contributions at a luminosity of 300 fb^{-1} at 13 TeV. Here, CP -even corresponds to $\kappa = 1$ and $\tilde{\kappa} = 0$, while CP -odd corresponds to $\kappa = 0$ and $\tilde{\kappa} = 1$. The expected numbers of events are reported after event selection in the $H \rightarrow \gamma\gamma$ final state.

Process	Cross section [fb]	Expected number of events
tWH (CP -even)	16.8	0.72
tWH (CP -odd)	69.5	3.99
$t\bar{t}H$ (CP -even)	509.0	16.91
$t\bar{t}H$ (CP -odd)	198.5	8.21

FIG. 5. The distributions of D_{0m} , D_{bkg} , and D_{int} . Four different scenarios are presented: the $pp \rightarrow tWH$ process with CP -even or CP -odd Yukawa couplings and the $pp \rightarrow t\bar{t}H$ process with CP -even or CP -odd Yukawa couplings.

To estimate the sensitivity in the $pp \rightarrow tWH$ process, we consider hadronic final states, where both the top quark and W boson decay hadronically, and $H \rightarrow \gamma\gamma$. This final state has a reasonable branching ratio and clean boson decays. The main background process is $pp \rightarrow t\bar{t}H$. Both $t\bar{t}H$ and tWH production are sensitive to the top quark Yukawa coupling, and the predicted cross sections at tree level are functions of κ and $\tilde{\kappa}$,

$$\sigma(\kappa, \tilde{\kappa})_{t\bar{t}H} = \sigma_{SM}^{t\bar{t}H}(|\kappa|^2 + 0.39|\tilde{\kappa}|^2),$$

$$\sigma(\kappa, \tilde{\kappa})_{tWH} = \sigma_{SM}^{tWH}(2.82|\kappa|^2 + 2.08|\tilde{\kappa}|^2 - 3.87\kappa + 2.05),$$

where $\sigma_{SM}^{t\bar{t}H}$ and σ_{SM}^{tWH} are the SM cross sections of $t\bar{t}H$ and tWH production, respectively.

We simulate tWH and $t\bar{t}H$ events using JHUGen. The parton shower and hadronization are implemented by Pythia8.1 and Delphes3 is used to simulate the CMS detector response.

For event selection, we require at least 5 jets with $p_T > 25$ GeV and $|\eta| < 2.4$, and exactly one b -tagged jet. Events with any isolated leptons or more than 8 jets are vetoed to remove $t\bar{t}H$ contributions. Two isolated photons are needed to pass the event selection criteria. The transverse momenta of the leading and subleading photons are required to have $p_T^1 > m_{\gamma\gamma}/3$ and $p_T^2 > m_{\gamma\gamma}/4$, respectively. To further suppress the $t\bar{t}H$ background, we require the transverse momentum of the Higgs boson to satisfy $p_T^H > 80$ GeV. The expected number of events of the signal and background processes at 300 fb^{-1} after selection are summarized in Table I. Other non-Higgs background processes like $t\bar{t} + \gamma\gamma$ may be distinguished by the invariant mass of the reconstructed Higgs boson, thus are not taken into account in this study.

We apply similar techniques as used in Sec. II to reconstruct the top quark in the final state. In total we build four matrix-element based discriminants: D_{0m} , D_{bkg} , D_{CP} , and D_{int} . The first two variables are of D_{alt} type as defined in Eq. (5). Model A and B are CP -even and

CP -odd model in D_{0m} , and are pure Htt diagram contribution and pure HWW contribution in D_{bkg} , respectively. D_{CP} and D_{int} are interference sensitive variables following the definition given in Eq. (6). D_{CP} is designed to detect the interference between CP -even and CP -odd Htt couplings, and D_{int} is to obtain the interference between HWW and Htt couplings. The distributions of D_{0m} , D_{bkg} , and D_{int} after event selection and reconstruction are presented in Fig. 5. The CP -even ($\kappa = 1$) and CP -odd ($\tilde{\kappa} = 1$) scenarios of tWH and $t\bar{t}H$ production are shown. CP -even and CP -odd tWH and $t\bar{t}H$ production are well separated in D_{0m} and D_{bkg} , and D_{int} is sensitive to the interference term of the tWH production. We use D_{0m} , D_{bkg} , and D_{int} to construct a 3-dimensional probability density function, which is fitted to the SM distribution to estimate the CP sensitivity. D_{CP} is only forward-backward asymmetric in models with CP violation as shown in shown in Fig. 6, thus not used for the SM sensitivity estimation. However it will be a very

FIG. 6. The distribution of D_{CP} of the $pp \rightarrow tWH$ process in three scenarios: $f_{CP} = 0$ (red), $f_{CP} = 0.5$ (blue), and $f_{CP} = -0.5$ (black).

powerful observable to detect any CP violation. Unlike in the $pp \rightarrow t\bar{t}H$ process, without using the decay information of the W boson and the top quark, the forward-backward asymmetry in $\mathcal{D}_{CP}$ remains in the tWH channel. This advantage of the $pp \rightarrow tWH$ process allows to probe the sign of the CP violation in all top quark and W decay modes.

IV. RESULTS

A maximum likelihood fit is performed in the $t\bar{t}$ and tWH events to quantify the sensitivity to the CP structure of the top quark Yukawa coupling. In this study, the Higgs boson coupling to other particles except the top quark are constrained to their SM value. The $H \rightarrow \gamma\gamma$ interaction could be modified by the top quark Yukawa coupling if we assume the loop is resolved. However, only the rates of tWH and $t\bar{t}H$ will be affected. As this study focuses on the kinematic effects on the Higgs production, we assume the $H \rightarrow \gamma\gamma$ rate is the same as the SM prediction. We present the results in two forms: one in terms of the Lagrangian coupling parameters κ and $\tilde{\kappa}$, and the other in terms of the CP -mixture parameter f_{CP} .

The expected likelihood scan results of κ and $\tilde{\kappa}$ at 300 fb^{-1} are shown in Fig. 7. The left and middle plots show the sensitivity using $t\bar{t}$ and tWH events, respectively. The right plot shows the expected sensitivity using tqH events, derived from Ref. [40]. It is clear from the middle and right plots that single top quark production provides sensitivity to the relative sign between the Htt and HWW coupling, while the $t\bar{t}$ plot is symmetric around $\kappa = 0$. This is expected as seen from Eqs. (2)–(4).

The sensitivities of the parameter f_{CP} at the luminosity of 300 fb^{-1} and 3000 fb^{-1} are shown in Fig. 8. When fitting the distributions in the f_{CP} framework, the overall signal rate is left unconstrained. This means whatever modification might enter $H \rightarrow \gamma\gamma$ is absorbed by this floating rate, thus the f_{CP} result is not affected by the assumptions in the

$H \rightarrow \gamma\gamma$ decay. The sensitivity using $t\bar{t}H$ and tqH presented in Ref. [40] are also shown for comparison. One should note that while tH dedicated studies aim to select tH events, $t\bar{t}H$ events enter the selection due to similar final state particles. These events contribute to the CP sensitivity in the tH channel as well. Without such background, the pure contribution from the tWH events are shown as a dashed line. The curve of $t\bar{t}$ reaches a plateau around $|f_{CP}| = 0.87$. This is where a switch between shape and rate effect comes into place. Beyond the boundary, the dominant effect is the overall change in the event rate with little kinematic shape variations, thus absorbed by the floating rate parameter.

The expected sensitivities show that $t\bar{t}$ and tH events are prone to different phase spaces. They could be complementary to each other in constraining the CP violation in top quark Yukawa coupling. Up to 300 fb^{-1} , they provide rather compatible 95% CL constraints. It will be interesting to see experimental results using all the processes.

The $pp \rightarrow t\bar{t}$ process is expected to exclude $|f_{CP}| > 0.81$ at 95% CL at the luminosity of 300 fb^{-1} . Although the total cross section of the tWH production in the SM is small, compared with the $t\bar{t}H$ and tqH production, this process can still exclude $|f_{CP}| > 0.68$ at 68% CL and exclude the pure pseudoscalar model at 2σ at a luminosity of 300 fb^{-1} . The results at a luminosity of 300 fb^{-1} can easily be projected to other luminosities such as 3000 fb^{-1} at the HL-LHC. At a luminosity of 3000 fb^{-1} , the $pp \rightarrow tWH$ process can exclude $|f_{CP}| > 0.48$ at 95% CL, and $|f_{CP}| > 0.67$ can be excluded by the $pp \rightarrow t\bar{t}$ process at 95% CL. Among the four processes, the tqH production, together with the $t\bar{t}H$ events entering the selection, gives most stringent 95% CL exclusion, which can exclude $|f_{CP}| > 0.68$ at a luminosity of 300 fb^{-1} and $|f_{CP}| > 0.22$ at a luminosity of 3000 fb^{-1} . For values of $|f_{CP}| > 0.8$, the $pp \rightarrow t\bar{t}$ process is the best candidate for exclusion at a luminosity of 3000 fb^{-1} .

FIG. 7. Two dimensional likelihood scans of κ and $\tilde{\kappa}$ in the $pp \rightarrow t\bar{t}H$ (left) and $pp \rightarrow tWH$ (middle) and $pp \rightarrow tqH$ (right) processes at a luminosity of 300 fb^{-1} . The expected 68% and 95% CL regions are presented as contours with dashed and solid black lines, respectively.

FIG. 8. The likelihood scan of f_{CP} at luminosity of 300 fb^{-1} (left) and 3000 fb^{-1} (right) with four processes shown: $pp \rightarrow t\bar{t}$, $pp \rightarrow tWH$, $pp \rightarrow t\bar{t}H$, and $pp \rightarrow tqH$. The red solid line shows the expectation considering tWH and the misreconstructed ttH events in the tWH channel, while the red dashed line assumes no contribution of ttH events in the tWH channel. The black and dark blue lines represent the 68% CL and 95% CL lines, respectively. The results of the $t\bar{t}H$ and tqH production are cited from Ref. [40].

V. SUMMARY

In this paper, we investigate the prospects of constraining the CP structure of the coupling of the Higgs boson to the top quark through electroweak loops in $t\bar{t}$ production. Sensitivity arises at loop level through off-shell degrees of freedom only. The fact that top quark pair production is the most dominant source of top quarks at the LHC while its theoretical description has reached impressive accuracy makes it the perfect candidate for such a novel study. To this end, we calculate $\mathcal{O}(\alpha)$ corrections to QCD induced $t\bar{t}$ production with arbitrary CP -even and CP -odd terms. Our results for the loop sensitivity are contrasted with the ones obtained from direct on-shell probes like Higgs production in association with a single top quark or a top quark pair. Our results show that loop sensitivity in $t\bar{t}$ is significantly stronger than on-shell sensitivity in associated production for CP -odd admixtures $|\tilde{\kappa}|/|\kappa| \geq 2.0$. Below that value, the $pp \rightarrow tqH$, $pp \rightarrow t\bar{t}H$, and $pp \rightarrow tWH$ processes are more sensitive. We hope that this work demonstrates the power of loop corrections and sparks new studies. For

example, in order to improve on modeling the impact of the electroweak corrections on the full kinematics in $t\bar{t}$ production, our results could be implemented in an event generator like JHUGen. This would allow for generation of unweighted events including electroweak corrections together with the respective weights for different Beyond Standard Model (BSM) hypotheses, making loop sensitivity studies possible with matrix element techniques like MELA. In addition, it would be interesting to extend our calculation to $e^+e^- \rightarrow t\bar{t}$ for future collider studies.

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