Boosting the Direct *CP* Measurement of the Higgs-Top Coupling

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Characterizing the 125 GeV Higgs boson is a critical component of the physics program at the LHC Run II. In this Letter, we consider $t\bar{t}H$ associated production in the dileptonic mode. We demonstrate that the difference in azimuthal angle between the leptons from top decays can directly reveal the CP structure of the top-Higgs coupling with the sensitivity of the measurement substantially enhanced in the boosted Higgs regime. We first show how to access this channel via $H \to b\bar{b}$ jet-substructure tagging, then demonstrate the ability of the new variable to measure CP. Our analysis includes all signal and background samples simulated via the MC@NLO algorithm including hadronization and underlying-event effects. Using a boosted Higgs substructure with dileptonic tops, we find that the top-Higgs coupling strength and the CP structure can be directly probed with achievable luminosity at the 13 TeV LHC.

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Determining the properties of the Higgs particle H at 125 GeV will provide important information about the as-yet unknown physics beyond the Standard Model (SM), and is therefore an important focus of the LHC Run II. Presently, its couplings to W and Z gauge bosons are directly measured through the Higgs decays to a vector boson pair and are consistent with a spin-0 particle with SM-strength CP-even couplings [1–5]. However, the ratios between scalar and pseudoscalar couplings might differ from channel to channel in the presence of CP violation. Hence, it is of fundamental importance to access this information in as many channels as possible (CP-odd Higgs-vector boson couplings can appear only through operators of dimension 6 or higher [6], while CP-odd Higgs-fermion couplings could manifest at tree level. Thus, the latter are naturally more sensitive to CP violation than the former). Of particular interest is the coupling to top quarks, as $y_t^{\mathrm{SM}} \sim \mathcal{O}(1)$.

The strength and CP structure of the top-Higgs coupling are currently inferred from the measured Higgs-gluon and Higgs-photon interactions through the production $gg \to H$ and decay $H \to \gamma\gamma$ channels [7,8], as well as constraints on electron dipole moments [9]. However, as these couplings are loop induced, the measurements could be a combination of SM and new physics [10,11]. Direct measurements of both the strength and CP properties of this coupling are necessary to disentangle new physics effects. The associated Higgs boson with $t\bar{t}$ pair production qualifies as the most direct probe.

In this Letter, we demonstrate that the $t\bar{t}H$ channel can be measured with dileptonic top pairs and Higgs decay to $b\bar{b}$ via jet substructure [12–14] (to our knowledge, this Letter is the first to use boosted Higgs substructure associated to dileptonic top pair). Including higher order QCD effects to signal and backgrounds via the MC@NLO algorithm [15], we show that this channel can be probed with a reasonable luminosity in the Run II LHC. In the same channel we then consider the direct CP measurement of the Higgs-top coupling via spin correlations. The lab frame CP-sensitive variable we propose is $\Delta\phi_{\ell\ell}$: the difference in azimuthal angle around the beam axis of the top pair decay leptons. This is somewhat similar to observables proposed in previous works [16–21]. However, the CP sensitivity of $\Delta\phi_{\ell\ell}$ is enhanced at large Higgs transverse momentum p_{TH}. Fortunately for our purposes, this requirement dovetails nicely with the kinematic region required for jet substructure Higgs tagging. Thus, high-p_{TH} dileptonic $t\bar{t}H$ events have experimentally attractive properties both for initial discovery and CP-structure measurement.

We parametrize the top-Higgs interaction as

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha) t H, \tag{1}$$

where K is a real number and α a CP phase. The CP-even SM Higgs 0^+ particle is $(K, \alpha) = (1, 0)$, while $\alpha = \pi/2$ corresponds to a CP-odd 0^-.

In principle, the anatomy of the top-Higgs interaction can be revealed via spin correlations, both at the LHC [16,17] and a future e^+e^- collider [22]. In the other LHC-focused works, the proposed variable's sensitivity is washed out by experimentally required selection criteria. Analogously to the $t\bar{t}$ production studied in Ref. [23], distinct kinematic distributions exist in $t\bar{t}H$ production between the like-helicity $(t_L\bar{t}_L + t_R\bar{t}_R)$ and unlike-helicity $(t_L\bar{t}_R + t_R\bar{t}_L)$ top pairs. We adopt helicity conventions as in HELAS [24].

For our analytic argument, we will consider the distribution of top pairs in the $t\bar{t}H$ production. Without full top-quark reconstruction, such distributions are not directly accessible.

However, the spin correlations between the top pairs are passed on to the top decay products, which are correlated with the top spin axis. The charged lepton and d quark from the W-boson decay have the largest degree of correlation with the top quark spin axis [23]. Hence, experimentally accessible leptonic angular variables from dileptonic top decay (such as $\Delta\phi_{\ell\ell}$, which we will demonstrate contains CP information) can be used as an experimentally clean proxy for the more fundamental variables built from t and $\bar{t}$ momenta, such as $\Delta\phi_{tt}$, considered here.

To further simplify our analysis, we focus on the $q\bar{q}$-initiated s-channel production of the $t\bar{t}H$ state, though a nearly identical argument follows when considering s-channel gluon-gluon production. We further restrict our consideration to top-antitop pairs of mixed helicity, $t_L\bar{t}_RH$ and $t_R\bar{t}_LH$, which transform into themselves under CP. These apparently arbitrary choices will be justified shortly.

With incoming quark and antiquark momenta q_1 and q_2, outgoing top and antitop momenta k_1, k_2, and Higgs momentum p, the mixed helicity state matrix element is

$$\mathcal{M} \propto \frac{m_t[\bar{v}(q_2)\gamma^\mu u(q_1)][\bar{u}(k_1)P_{L/R}A\gamma_\mu P_{R/L}v(k_2)]}{[q_1+q_2]^2[m_H^2+2k_1\cdot p][m_H^2+2k_2\cdot p]},$$
$$A = \left[\frac{m_H^2}{2}+(k_1+k_2)\cdot p\right]\cos\alpha - i[(k_1-k_2)\cdot p]\gamma_5\sin\alpha. \tag{2}$$

The matrix A is the only source of a possible kinematic difference resulting from the CP structure of the top-Higgs coupling. Of course, $\Delta\phi_{tt}$ (as with many other kinematic variables) will appear in other locations in the matrix element and phase space factors, but any kinematic difference arising from α must come from A.

The ideal set of kinematic variables measuring α in the mixed helicity top final state is one that is maximally sensitive to both $(k_1+k_2)\cdot p$ and $(k_1-k_2)\cdot p$. Unfortunately, using these kinematic combinations directly requires full event reconstruction, which is challenged by jet energy uncertainties and missing energy in the leptonic decays [25]. Our chosen variable $\Delta\phi_{tt}$ inhabits a happy medium, probing $(k_1\pm k_2)\cdot p$ as we will show, while being closely related to the easily measured $\Delta\phi_{\ell\ell}$.

The dependence on $\Delta\phi_{tt}$ in the coefficients of Eq. (2) is maximized in the high-momentum regime. Performing a boost along the beam axis (which leaves $\Delta\phi_{tt}$ unchanged) to the frame where the Higgs boson is perpendicular to the beam, the coefficients can be written in terms of the sum of the top-antitop azimuthal angles Σ_{tt} and their difference $\Delta\phi_{tt}$. We see that we can approximate

$$(k_1+k_2)\cdot p \propto \sin\left(\frac{\Delta\phi_{tt}}{2}\right)\cos\left(\frac{\Sigma_{tt}}{2}\right) - \frac{1}{2}\sin\Delta\phi_{tt}, \tag{3}$$

$$(k_1-k_2)\cdot p \propto \cos\left(\frac{\Delta\phi_{tt}}{2}\right)\sin\left(\frac{\Sigma_{tt}}{2}\right) - \frac{1}{2}\sin\Sigma_{tt}. \tag{4}$$

The key observation here is that the CP-even couplings oscillates with sines of $\Delta\phi_{tt}$, and the CP-odd couplings with cosines. Integrating over Σ_{tt}, we see that the CP-even (odd) coupling has a deficit of events at $\Delta\phi_{tt}=0(\pi)$ and an excess at $\pi(0)$. The form of this result can also be obtained by considering the interference between spin states [26], and requiring that the mixed helicity states transform as $(-1)^j$ for the CP-even couplings and $(-1)^{j+1}$ for the CP odd, for total angular momentum j.

This analytic argument is borne out in simulation, using the full matrix element calculation, all initial state partons (not just quark or antiquarks), and summing over all helicities. Figure 1 shows the differential distribution $\Delta\phi_{tt}$ with and without the large Higgs $p_{\rm TH}$ cut. At low $p_{\rm TH}$, $\Delta\phi_{tt}$ has a minimum at ~ 0 and peaks at $\sim\pi$ for both CP-even and CP-odd couplings. However, at the high $p_{\rm TH}$ regime and in the unlike-helicity $t\bar{t}H$ final states, the CP sensitivity of $\Delta\phi_{tt}$ becomes clear. As in our analytic argument, these helicity combinations develop peaks at $\Delta\phi_{tt}\sim 0$ and a minimum at $\sim\pi$ for the CP-odd coupling, opposite to the

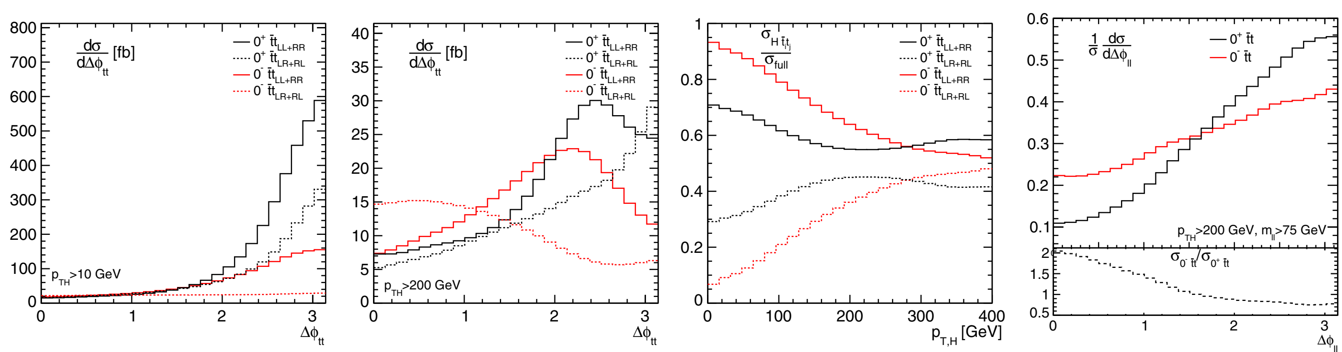

FIG. 1. Left and left-center: $\Delta\phi_{tt}$ distribution for CP-even 0^+ (black) and CP-odd 0^- (red) couplings without requiring a boosted Higgs boson (left panel) and in the boosted regime $p_{\rm TH} > 200$ GeV (left-center). Contributions from the like-helicity $t_L\bar{t}_L + t_R\bar{t}_R$ and unlike-helicity $t_L\bar{t}_R + t_R\bar{t}_L$ states are shown in solid and dashed lines, respectively. Right-center: Fraction of like-helicity and unlike-helicity states as a function of the minimum Higgs transverse momentum selection cut $p_{T,H}$. Right: $\Delta\phi_{\ell\ell}$ parton-level distribution for CP-even and CP-odd Higgs with $p_{\rm TH} > 200$ and $m_{\ell\ell} > 75$ GeV.

distributions for the other final states. Fortunately, the high $p_{\rm TH}$ regime also enhances the signal-containing mixed helicity configuration [19]. As seen in Fig. 1 (right-center), the unlike-helicity fraction goes from ~7% (30%) of the cross section at low $p_{\rm TH}$ selection to ~40% (45%) at $p_{\rm TH} > 200$ GeV for the CP-odd (-even) state.

The right panel of Fig. 1 shows the differential $\Delta\phi_{\ell\ell}$ distribution in the CP-even and CP-odd scenarios with $p_{\rm TH} > 200$ and $m_{\ell\ell} > 75$ GeV. This second requirement is a proxy for m_{tt}, further enhancing the unlike-helicity final states [23]. As with $\Delta\phi_{tt}$, the behavior of the 0^- coupling is clearly distinguished from the 0^+ assumption by an increase in events near $\Delta\phi_{\ell\ell} \sim 0$ and a deficit near π.

Requiring Higgs boson $p_{\rm TH} > 200$ GeV is a sacrifice of total cross section. However, in our analysis, we consider the $t\bar{t}H$ channel with dileptonic top decay and Higgs decay to $b\bar{b}$. As we will describe, jet-substructure tagging can be used in this channel to distinguish the signal from the background. Requiring collimated b quarks in a fat-jet [12,13] implies a large boost for the Higgs boson. Our CP-sensitive signal is enhanced with the same kinematics required for background rejection.

We now turn to the question of realistic event selection, background rejection, and required luminosity. We first show that we can assess this channel at the Run II LHC and then that we can directly probe its CP structure.

We consider the Higgs top in $pp \to t\bar{t}H$ with dileptonic tops and the Higgs boson decay $H \to b\bar{b}$ at the $\sqrt{s} = 13$ TeV LHC. We demand four bottom tagged jets and two opposite-sign leptons. The main backgrounds for this process in order of relevance are $pp \to t\bar{t}b\bar{b}$ and $t\bar{t}Z$.

The signal $t\bar{t}H$ sample is generated with MadGraph5 +Pythia8 [27,28], and the $t\bar{t}b\bar{b}$ and $t\bar{t}Z$ backgrounds with Sherpa+OpenLoops [29,30]. All signal and background samples are simulated with the MC@NLO algorithm [15] and account for hadronization and underlying event effects. Since the Higgs boson is part of a multijet system, a proper modeling of QCD effects is fundamental in this study. Hence, we include the higher order QCD contributions to all considered processes.

Next-to-leading-order (NLO) process generation requires factorization between the $t\bar{t}H$ production and decays. Spin correlations are restored in our simulations by MadSpin [31] and the respective Sherpa module [32]. Their outputs were in agreement at leading order with a full decay chain simulation.

Our search strategy relies on the background suppression at the boosted regime [12–14], which opportunely enhances the desired spin correlation effects, as previously mentioned. We start our analysis with some basic leptonic selections: two isolated opposite-sign leptons with $p_{T\ell} > 15$ GeV and $|\eta_\ell| < 2.5$. The hadronic part of the event uses the Cambridge/Aachen (C/A) jet algorithm [33], and requires at least one boosted ($p_{TJ} > 200$ GeV) and central ($|\eta_J| < 2.5$) fat jet ($R = 1.2$). This must be Higgs tagged via the BDRS algorithm [12,13], requiring three subjets where the two hardest are b tagged. We assume 70% b-tagging efficiency and a 1% mistag rate [34]. Possible pileup effects on the Higgs mass are controlled by the BDRS filtering, as it has been shown on LHC data [35]. After a successful Higgs tag, we remove the Higgs fat jet from the event and recluster the remaining hadronic activity with C/A using a smaller jet radius $R = 0.5$. As the signal does not have any additional high mass particle decaying hadronically, we can safely suppress the underlying event contamination by decreasing the jet size. We then demand at least two jets with $p_{Tj} > 30$ GeV and $|\eta_j| < 2.5$, at least two of which are b tagged.

TABLE I. Cut flow for signal and backgrounds at LHC $\sqrt{s} = 13$ TeV. The selection follows the BDRS analysis described in the text. Rates are in fb and account for 70%(1%) b-tag (mistag) rate, hadronization, and underlying event effects.

Cuts	$t\bar{t}H$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$
BDRS H-tag, $p_{T\ell} > 15$ GeV, $\lvert\eta_\ell\rvert < 2.5$ $p_{Tj} > 30$ GeV, $\lvert\eta_j\rvert < 2.5$, $n_j \geq 2$, $n_l = 2$	1.19	10.93	1.11
Two extra b tags (four in total)	0.43	4.21	0.21
$\lvert m_H^{\rm BDRS} - m_H\rvert < 10$ GeV, $m_{b\bar{b}} > 110$ GeV	0.077	0.111	0.003
$m_{\ell\ell} > 75$ GeV	0.056	0.082	0.003

To enhance the signal/background (S/B) ratio and suppress combinatorics, we require that the reconstructed mass for the filtered Higgs be in the window $|m_H^{\rm BDRS} - m_H| < 10$ GeV and the filtered b-tagged jets to have $m_{b\bar{b}} > 110$ GeV. The detailed cut flow is presented in Table I.

As for the $t\bar{t}H$ analysis with hadronic top decays, $S/B < 1$ [13]. The bounds can be improved by accounting for the signal and background distribution profiles. We use the two-dimensional distribution $(p_{\rm TH}, \Delta\phi_{jj})$ for our log-likelihood

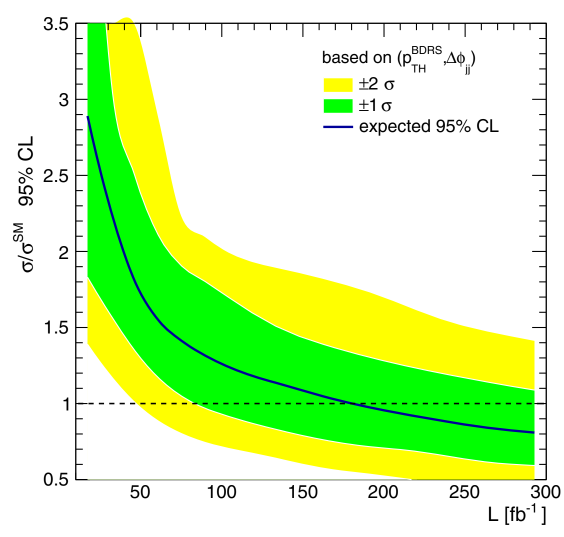

FIG. 2. Expected 95% C.L. upper limits on $\sigma/\sigma^{\rm SM}$ for four b-tag dileptonic $t\bar{t}(H \to b\bar{b})$ as a function of LHC luminosity.

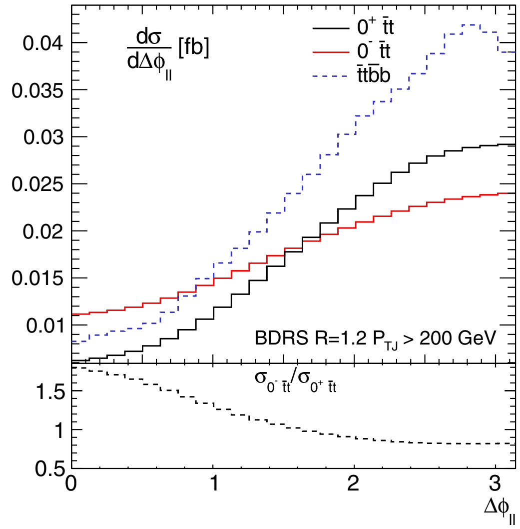

FIG. 3. Azimuthal correlation between the two leptons $\Delta\phi_{\ell\ell}$ calculated in the lab frame after the BDRS analysis.

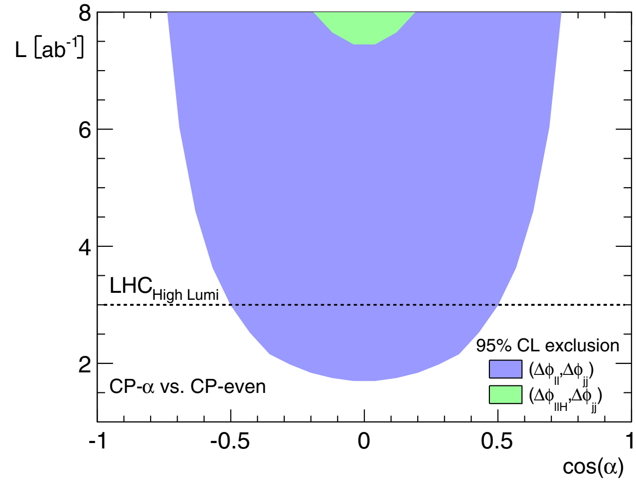

FIG. 4. Luminosity required to distinguish CP-even $t\bar{t}H$ coupling from couplings with arbitrary CP phase.

test. The p_{TH} distribution drops slower for signal than for the continuum background. This is the main reason to look at the boosted kinematics for this signal. In addition, the azimuthal angle between the two leading jets $\Delta\phi_{jj}$ (either b tagged or not) presents a different profile thanks to the different radiation profiles of signal and background. In Fig. 2 we present the expected 95% C.L. limit on the signal strength $\sigma/\sigma^{\rm SM}$ in the dileptonic $t\bar{t}H$ channel as a function of the LHC luminosity. Sensitivity to the SM coupling will require $\sim$175 fb^{-1} of integrated luminosity. Additional improvements for the signal extraction can be achieved, e.g., via the matrix element method or a neural network [36,37].

Next we consider CP discrimination in the Higgs-top coupling. We further require the dilepton invariant mass to be $m_{\ell\ell} > 75$ GeV, enhancing the sensitivity of $\Delta\phi_{\ell\ell}$ from $\sigma_{0^-t\bar{t}}/\sigma_{0^+t\bar{t}} \sim 1.4$ to ~ 1.9 at $\Delta\phi_{\ell\ell} \sim 0$. After all cuts, the CP-even and CP-odd distributions of $\Delta\phi_{\ell\ell}$ (and $t\bar{t}b\bar{b}$ background) are shown in Fig. 3. Note that this remains sensitive to the Higgs-top CP structure after a realistic simulation that includes, in particular, NLO QCD effects.

To analyze $\Delta\phi_{\ell\ell}$'s discriminating power, we perform a binned log-likelihood test in $(\Delta\phi_{\ell\ell}, \Delta\phi_{jj})$. To focus only on measurement of α, we fix the number of signal events to the SM prediction. In Fig. 4, we plot the expected statistical significance with which this analysis can distinguish a top-Higgs coupling with arbitrary CP phase from the CP-even $\alpha = 0$ case. As can be seen, 95% C.L. exclusion of the CP-odd case should be possible with $\sim$1.8 ab^{-1} of data, and the high luminosity LHC would be able to distinguish the CP-even couplings from couplings with $|\cos\alpha| \lesssim 0.5$. This bound can be further improved by using more observables in our likelihood test and by including the three b-tag sample.

In Fig. 4, we also compare our analysis with another lab-frame observable proposed in Ref. [17]. Here the angle is defined around the Higgs axis: $\Delta\phi_{\ell\ell H}$. We notice that the CP sensitivity of this observable decreases in the boosted regime in comparison with $\Delta\phi_{\ell\ell}$.

In this Letter, we have introduced a simple lab-frame variable $\Delta\phi_{\ell\ell}$, which can be used to measure the CP properties of the top-Higgs coupling in the dileptonic channel. On theoretical grounds, we expect this variable to be most useful when the Higgs is significantly boosted, which pushes us into a kinematic regime where significant reductions in background can be obtained via substructure tagging when H decays to $b\bar{b}$. The high-p_{TH} kinematic regime, where $\Delta\phi_{\ell\ell}$ is most sensitive to CP, also lends itself to a boosted Higgs analysis, which can be used to significantly enhance the discovery potential of the $t\bar{t}H$ channel. We show a detailed theoretical study at NLO in the four b-tag sample, demonstrating that the LHC with $\sqrt{s} = 13$ TeV should be capable of probing the SM-strength top-Higgs coupling with $\sim$175 fb^{-1}, and then distinguishing between the CP-even and CP-odd couplings with $\sim$1.8 ab^{-1}. Improvements may be possible, for example, by including the three b-tag sample, or adding additional discriminating variables.

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