Top polarization as a probe of CP -mixing top-Higgs coupling in tjh signals

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In this paper, we explore beyond the Standard Model top-Higgs Yukawa couplings as a function of a CP -mixing parameter ξ_t at the 14 TeV HL-LHC in the process $pp \rightarrow thj$. We observe that angular variables of the decay products of the top are nontrivially sensitive to ξ_t . This fact is exploited in a full detector level analysis that employs machine learning techniques to optimize signal sensitivity on a suite of variables, including lepton azimuthal angle. The key result of this study is an improved projected exclusion limit on ξ_t even when including the realistic effects of detector smearing and a conservative estimate of systematic error.

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I. INTRODUCTION

Since the discovery of a scalar particle at 125 GeV as predicted by the Standard Model (SM) at the Large Hadron Collider (LHC) in 2012 [1,2], attention has turned to narrowing down its properties. It is of great interest as to whether this particle behaves exactly as the SM predicts or if it is perhaps a beyond the SM (BSM) scalar that exists within an expanded Higgs sector.

The measurement of the Higgs couplings to fermions is an on-going area of research as many of these couplings can be small and require large luminosities to probe, which motivates the application of intelligent analysis techniques to probe the signal as optimally as possible. The Higgs coupling to the top is of particular interest as it is the largest, and so far, the $t\bar{t}h$ coupling is probed via the loop-induced processes hgg and $h\gamma\gamma$, which rely on decay rate measurements of the Higgs boson. It is well known that the production cross section of both hgg and $h\gamma\gamma$ will be sensitive to a phase ξ_t of the top Yukawa coupling [3]. This phase mixes the CP properties of the top-Higgs coupling and thus, is CP violating. Assuming only the CP phase and keeping the SM value for magnitude, strong constraints could be placed on the phase. However, those processes can only occur at a one-loop level and beyond. Noting that new physics dynamics can contribute in the loop and thus,

may affect the accurate determination of top-Yukawa phase, the Higgs production in association with a top pair (dominant) and the Higgs boson produced with a single top (subdominant) are the only means to directly probe this coupling. These processes have been established at above 5σ in Refs. [4,5]. It is found that increasing $|\xi_t|$ leads to a suppression of the $t\bar{t}h$ cross section and an enhancement of the tjh cross section [6,7].

A study of this process has also been undertaken utilizing the matrix-element-method (MEM) which shows that, with signal detection efficiencies on the order of a few percent, discovery could be made in the high luminosity phase of the LHC [8]. Also, it has been shown in Ref. [9] using matrix element techniques that 3σ separation of the pseudoscalar vs scalar $t\bar{t}h$ coupling can be realized with 300 fb^{-1} of data.

Further phenomenological studies of the top-Higgs coupling can be found in Refs. [10–15].

The top quarks lifetime is so short that it decays before hadronization, meaning that its polarization information is preserved in the distribution of its decay products which can be measured directly by the detector, especially in its lepton angular distributions. In many new physics scenarios, it has been shown extensively in literature, Refs. [16–25], that charged-lepton azimuthal distribution is a powerful probe of top quark polarization in the lab frame. There are two advantages of studying the charged lepton azimuthal distribution: first, it does not require reconstruction of the top-rest frame, which would need full information of top-quark momentum and second, it is unaffected by any new physics in the top-quark decay and thus, making it an uncontaminated probe of top quark polarization. This variable is constructed by taking the azimuthal angle of the lepton decaying from the top with respect to the x - z plane, where the top quarks x component

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is positive. For other methodologies of studying top polarization, see Refs. [13,26,27].

Top quark polarization can be written in terms of ξ_t [28,29], and thus, the decay products differential distributions will be affected by ξ_t , allowing for the improvement of analysis of this process. This has been exploited in a range of studies [28–30]; however, these have not been undertaken at a detector level to provide more accurate reflections of achievable sensitivity. Furthermore, these studies have employed traditional cutflow methods rather than more modern and advanced machine learning (ML) techniques to optimize signal sensitivity. In this paper, we employ a full detector level analysis to calculate the angular variables of the decay products of the process $pp \rightarrow thj$ with the optimization of signal sensitivity through ML algorithms.

This paper is structured as follows: Sec. II will cover the parametrization of the top-Higgs coupling and its implementation, Sec. III will outline signal and backgrounds, Sec. IV will outline event simulation and reconstruction, Sec. V will present the results of this analysis, and finally, we will conclude in Sec. VI.

II. CP-MIXED TOP-HIGGS COUPLING

In this study, a CP -mixing parameter ξ_t is introduced in the mass basis of the top-Higgs sector via the Lagrangian,

$$\mathcal{L}_{tth} = -\frac{y_t}{\sqrt{2}} \bar{t}(\cos \xi_t + i\gamma_5 \sin \xi_t)th. \quad (1)$$

The SM limit corresponds to when the mixing angle $\xi_t = 0$ and the Yukawa coupling adopts its SM value $y_t \rightarrow y_t^{\text{SM}} = \sqrt{2}m_t/v$, where m_t is the mass of the top and $v \simeq 246$ GeV is the standard model Higgs vacuum expectation. We adopt a model independent approach in which the interaction Lagrangian in Eq. (1) arises from an effective field theory (EFT), such as the dimension-6 operators discussed in Refs. [31–35]. We assume that the new physics scale Λ of such an EFT is $\gtrsim 1$ TeV with couplings of $\mathcal{O}(1)$, such that the mixing angle $\xi_t \in (-\pi, \pi]$ [36].

Constraints on y_t and ξ_t from the hgg and $h\gamma\gamma$ loop processes can be found in Refs. [7,28,37–41]. Further constraints including unitary violation in W and Z scattering with the top have been defined in Refs. [42,43]. The strongest constraints come from precision electron dipole-moment (EDM) measurements [44–46]; however, these are done under assumptions which when relaxed allow for much looser constraints. Assuming a standard model value for y_t , collider constraints have rendered $\xi_t \in [0, 2\pi/3]$ at 2σ [47]. For this study, we also assume that y_t and WWh coupling adopt standard model values. Furthermore, for the sake of completeness, we perform the study on the entire region $\xi_t \in [0, \pi]$.

FIG. 1. Feynman diagrams for the dominant production process $bq \rightarrow thj$.

III. SIGNAL AND BACKGROUND

The process studied is Higgs production with an associated top quark and jet, $pp \rightarrow tjh$, at the 14 TeV LHC. Figure 1 displays the dominant Feynman diagrams contributing to signal production.

Due to the extremely clean signature it provides, the decay mode of $h \rightarrow \gamma\gamma$ has comparable signal sensitivity to the $h \rightarrow b\bar{b}$ decay despite a much smaller branching ratio. We hence choose this decay mode of the Higgs boson for our analysis. In Fig. 2, one can see the effect of the CP -mixing parameter ξ_t on the production cross section of tjh . This effect is in agreement with previous results seen in Ref. [30] and contains a maximum enhancement at $\xi_t = \pi$ of approximately 1200%.

We demand a final state containing one b jet, exactly one lepton (but not τ), and at least two photons. The irreducible background for this process is the $tj\gamma\gamma$ continuum. The subleading background is $t\bar{t}\gamma\gamma$, where a b jet is lost, i.e., mistagged as a light jet or produced outside acceptance. The background $Wjj\gamma\gamma$ where a light jet is mistagged as a b jet exists; however, it is found to be at least an order of magnitude lower than the previous two backgrounds [6,48] and is ignored in this study. Finally, the backgrounds $t\bar{t}jj$ and $t\gamma jj$ are neglected in this study as they would require

FIG. 2. The production cross section (red) and production cross section times $h \rightarrow \gamma\gamma$ branching ratio (blue) normalized with respect to standard model values for $\xi_t \in [0, \pi]$.

the misidentification of a light jet as a photon, which suppresses the already small cross section.

IV. EVENT SIMULATION AND RECONSTRUCTION

The parton level events are produced in MG5_aMC_v2_6_0 [49] then passed to PYTHIA8 [50] for hadronization/fragmentation, and finally, DELPHES [51] for detector effects. Each sample consists of 100,000 events, achieving an MC uncertainty on inclusive cross section values that is on the order of 0.1%.

We employ anti-kt jet clustering and take a b -tag efficiency of 77%, a mistagging efficiency of 1%, and a lepton selection efficiency of 100%. We also employ the following detector acceptance cuts:

$$p_T^{b,\ell} > 20 \text{ GeV}, \quad |\eta_{b,\ell}| < 2.5, \quad p_T^j > 25 \text{ GeV}, \quad |\eta_j| > 2.5. \quad (2)$$

The cut on $|\eta_j|$ is employed to take advantage of the forwardness of the light jet which is characteristic of the tjh signal.

As we are selecting exactly one lepton, we are able to calculate the longitudinal momentum of the neutrino decaying from the top. We do this using the following quadratic equation:

$$p_{\nu}^z = \frac{1}{2p_{\ell T}^2} \left(A_W p_{\ell}^z \pm E_{\ell} \sqrt{A_W^2 \pm 4p_{\ell T}^2 E_{\nu T}^2} \right), \quad (3)$$

where, $A_W = M_{W^\pm}^2 + 2p_{\ell T} \cdot E_{\nu T}$. We choose the solution for p_{ν}^z that is real and that when combined with the remainder of the neutrino and lepton four-vector components produces an invariant mass closest to the W boson mass. After this is done, the top quark is reconstructed from the neutrino, the lepton, and the b jet, which best reproduces the top quark invariant mass.

In Fig. 3, we present the variables selected for the numerical analysis to come. In the ℓ_0^ϕ plot (upper right of each subfigure), the lepton azimuthal distribution generated from the prescription above can be seen for the hardest lepton in each event. It is clear that the value of ξ_t is impacting this distribution significantly as the SM value of $\xi_t = 0$ presents a distribution identical to the background while the fully CP -odd value of $\xi_t = \frac{\pi}{2}$ presents a far more skewed distribution. In addition, the variables show that the reconstruction is faithfully producing invariant mass distributions for the top quark and Higgs boson.

V. RESULTS

As seen in Ref. [30], we can construct the lab frame left-right asymmetry of the charged lepton using

FIG. 3. Examples of variables employed in the analysis for the $\xi = 0$ (a) and $\xi = \frac{\pi}{2}$ (b) benchmarks.

$$A_{\phi}^{\ell} = \frac{\sigma(\cos \phi > 0) - \sigma(\cos \phi < 0)}{\sigma(\cos \phi > 0) + \sigma(\cos \phi < 0)}. \quad (4)$$

Figure 4 displays this asymmetry as a function of ξ_t , which takes a maximum at $\xi_t = \frac{\pi}{2}$. However, when compared to the parton level calculation of this asymmetry found in Ref. [30], it can be seen that the detector effects lead to a flattening of this curve.

Standard cut flows for this signal have been performed in the past such as in Refs. [29,30], and thus, we do not perform one in this work. Instead, we employ a boosted

FIG. 4. The A_{ϕ}^{ℓ} asymmetry as a function of ξ_t for the signal and background.

TABLE I. Table of signal sensitivity defined as: $Z = S/\sqrt{S+B+(\Delta B)^2}$ after applying the optimized cut generated by BDT analysis. A luminosity of 3000 fb^{-1} is chosen, and the number of background events before cuts is $N_b^b = 1076$.

ξ_t	N_s^b	Cut	N_s^a	N_b^a	Z	$Z_{0.2}$
0	8	0.1146	7	21	1.28	1.04
$\frac{\pi}{4}$	23	0.0910	20	24	3.05	2.44
$\frac{\pi}{2}$	89	0.0819	83	27	7.92	7.04
$\frac{3\pi}{4}$	198	0.0317	191	35	12.70	11.52
π	255	0.0503	244	34	14.64	13.55

decision tree analysis on the variables found in Fig. 3 using the toolkit for multivariate data analysis (TMVA) [36].

Table I presents the boosted decision tree (BDT) results for each value of ξ . The column labels are as follows: N_s^b is the number of signal events before cuts while N_s^a and N_b^a are the number of signal and background events after cuts, respectively. The number of background events before cuts was $N_b^b = 1076$. The column labeled “Cut” is the position of the optimal cut on the BDT classifier distribution. σ is the signal sensitivity considering no systematic error, while $\sigma_{0.2}$ is the signal sensitivity with a flat 20% systematic error. The systematic error of 20% was taken as an estimate of the overall level of systematic error in typical one-lepton plus jets final state experiments [52]. The results presented in this table show, as expected, high values of $\xi_t \geq \frac{\pi}{2}$ are strongly inconsistent with background only. The 95% C.L. exclusion of approximately $\xi_t = 0.54$ without systematic and $\xi_t = 0.68$ with systematic is expected for 3 ab^{-1} of data at the HL-LHC, a significant improvement on the $\xi_t = 0.79$ exclusion placed in Ref. [30]. We also see an improvement over the HL-LHC results found in Ref. [13]. The parametrization in this work allows for complete freedom of the CP -even and CP -odd contributions to the top-Higgs coupling, called κ and $\tilde{\kappa}$, respectively. A detector level analysis using optimized angular variables is performed in the semileptonic final state, and only the top pair background is considered. A significance value of $S/\sqrt{B} \approx 0.8$ for (it is assumed) the SM value of $\tilde{\kappa}$ utilizing a semileptonic final state is found, and no meaningful bound on $\tilde{\kappa}$ can be extracted. The improvements

are likely due to a combination of the BDT analysis and the additional top polarization variable included. It is likely that had this analysis been undertaken at parton level like previous analyses of this process, then improvements on the constraints would be even larger, that is to say that detector effects have likely reduced the overall positive impact of the BDT analysis and top polarization variable.

VI. CONCLUSION

The direct detection of top-Higgs coupling has now been achieved via the process $pp \rightarrow t\bar{t}h$; however, the properties of this coupling still require further study. The process $pp \rightarrow tjh$ provides a good window into the charge-parity properties of the coupling as increasing values of the top-Higgs coupling phase ξ_t lead to increased cross sections, while the $t\bar{t}h$ process experiences decreases.

In this work, we have introduced a CP -mixing parameter ξ_t to the SM top-Higgs coupling via an effective operator. We have explored the well studied effects of this variable on top and jet associated Higgs production. Previous studies were then expanded on by performing a full detector level analysis of this process, including the variable defined from the azimuthal distribution of the lepton decaying from the top, which provides a powerful insight into top polarization. Results were then further improved via the application of a ML algorithm, namely boosted decision tree analysis, to optimize signal sensitivity.

The key result of this study is a projected 95% median exclusion of $\xi_t \leq 0.54$ when not considering systematic errors and $\xi_t \leq 0.68$ when considering a conservative level of systematic error with 3 ab^{-1} of luminosity, a significant improvement over previous analyses of this process. It is reasonable that the HL-LHC can provide very strong limits on ξ_t even in pessimistic scenarios.

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