

Study of the $C\mathcal{P}$ properties of the top-quark Yukawa interaction in $t\bar{t}H$ and tH events with $H \rightarrow \gamma\gamma$

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These proceedings present the first search for $C\mathcal{P}$ -violation in the top-Yukawa coupling using $t\bar{t}H$ and tH production modes in the diphoton decay channel ($H \rightarrow \gamma\gamma$). The analysis is based on the 139 fb^{-1} of proton-proton collision data at center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ recorded with the ATLAS detector at the Large Hadron Collider. Two separate set of selections are introduced to capture the full hadronic and leptonic decay of the $t\bar{t}$ system each. This search is performed using a simultaneous fit to the diphoton invariant mass distribution in analysis categories defined to enhance signal over continuum background and also to separate the $C\mathcal{P}$ -even and $C\mathcal{P}$ -odd signal hypotheses.

*** *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. Introduction

The study of the interaction of the top quark with the Higgs boson is key to probe Higgs properties such as the charge conjugation and parity (CP) of this coupling. For this, the production of the Higgs boson in association with top quarks at the LHC [1, 2] presents the first opportunity to directly study top-Higgs interactions. The Standard Model (SM) predicts a scalar Higgs ($J^{CP} = 0^{++}$) with a prescribed coupling to the top quark. However, the presence of a $J^{CP} = 0^{+-}$ pseudoscalar admixture, which introduces a second coupling to the top quark, has not yet been excluded. The observation of this CP -odd contribution would be a sign of beyond the SM physics.

There are two main processes to explore the CP properties of the top-Yukawa coupling: the $t\bar{t}H$ and the tH production. The CP -odd component impacts the production rates and some kinematic distributions. This effect can be seen in Figure 1 for the mentioned processes as well as for the $H \rightarrow \gamma\gamma$ branching ratio and the ggF production.

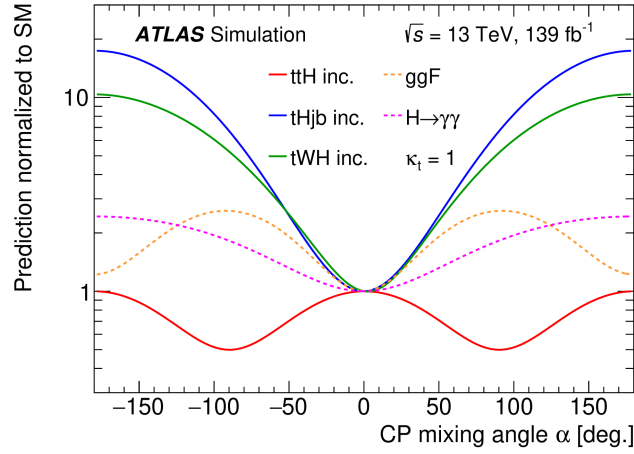


Figure 1: Dependence of the expected rates on the mixing angle for $\kappa_t = 1$. Normalised to the SM expectation. Figure from Ref. [3].

This analysis is performed using 139 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton (pp) collision data recorded from 2015 to 2018 with the ATLAS detector [4–6]. The effective field theory (EFT) definition to introduce a CP -odd component in the top-Yukawa coupling is provided by the Higgs characterization model [7], which is implemented in the MADGRAPH5_AMC@NLO generator [8]. Within this model, the term in the effective Lagrangian that describes the top-Yukawa coupling is

$$\mathcal{L} = -\frac{m_t}{v} \{ \bar{\psi}_t \kappa_t [\cos \alpha + i \sin \alpha \gamma_5] \psi_t \} H, \quad (1)$$

where m_t is the top quark mass, v is the Higgs vacuum expectation value, $\kappa_t (> 0)$ is the top-Yukawa coupling parameter, and α is the CP -mixing angle. The term proportional to $\sin \alpha$ introduces the CP -odd interaction.

2. Event Selection and Categorisation

Events are required to have two isolated photons (decaying from the Higgs boson) with transverse momenta (p_T) greater than 35 GeV and 25 GeV. Both photons must satisfy the tight identi-

fication requirement [9]. In addition, events are separated into two $t\bar{t}H$ -enriched regions. In first place, the ‘‘Lep’’ region ($\geq 1j, \geq 1b$) includes events where a W boson (from a top quark decay) will decay leptonically. Secondly, the ‘‘Had’’ region ($0l, \geq 3j, \geq 1b$) will include all other events with hadronically decaying W bosons. These two additional jets must have a $p_T > 25$ GeV. An object-level boosted decision tree (BDT) ‘‘Top Reco BDT’’ is trained with the $t\bar{t}H$ sample by using the XGBoost package [10] to extract a top quark candidate. Its goal is to separate between random jet triplets from $t\bar{t}H(\gamma\gamma)$ events from those coming from a top quark decay. The BDT uses information from the decay products of the top quark (W boson and b -jet) from reconstructed jets or the final-state lepton for the ‘‘Had’’ and ‘‘Lep’’ regions respectively. Figure 2 shows the reconstructed top quark candidate mass from the BDT.

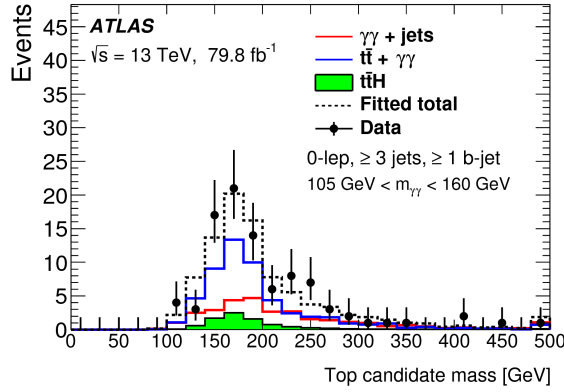


Figure 2: Distribution of the reconstructed top quark-candidate in the diphoton mass window from a triplet of jets selected by the dedicated ‘‘Top Reco BDT’’. There is a good agreement with data. Figure from Ref. [1].

To improve the analysis sensitivity, selected events are categorized using partitions of a two-dimensional BDT space. Two additional BDTs are trained separately in both the ‘‘Lep’’ and ‘‘Had’’ channels:

- **Background BDT** aims to separate between $t\bar{t}H$ signal and background events [1]. It exhibits good background rejection and $t\bar{t}H/tH$ acceptance and weak dependence with $C\mathcal{P}$ -mixing angle.
- **CP BDT** aims to separate $C\mathcal{P}$ -even for $C\mathcal{P}$ -odd events.

Figure 3 shows the BDT discriminant distributions in the data as well as those expected from $C\mathcal{P}$ -even and $C\mathcal{P}$ -odd Higgs boson signals in the ‘‘Had’’ region. There are 20 categories in total: 12 in the ‘‘Had’’ region and 8 in the ‘‘Lep’’ region.

3. Fitting Procedure and Results

A simultaneous maximum-likelihood fit is performed to the diphoton invariant mass ($m_{\gamma\gamma}$) spectra in all the categories. Signal and background shapes are modeled by analytic functions as discussed in Ref. [11]. Figure 4 shows the distributions of the reconstructed masses for the diphoton system and primary top quark. Figure 5 shows the yields for the $C\mathcal{P}$ -even and $C\mathcal{P}$ -odd signals

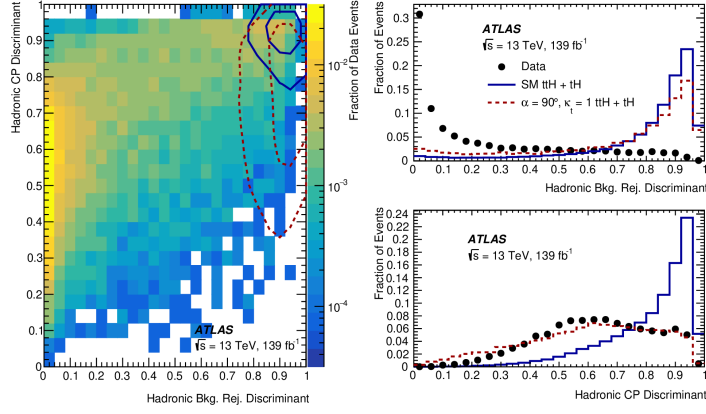


Figure 3: Two dimensional BDT distribution for the hadronic channel (left). Inner (outer) contours capture 25% (50%) of $t\bar{t}H$ and tH signal events. Projections to Background and CP BDT axes normalized to unity (right). Figure from Ref. [3].

as well as the data calculated in the smallest $m_{\gamma\gamma}$ interval containing 90% of the signal shown in three groups of categories. The binning is obtained by the combination of the appropriate event categories defined from the previous BDT categorisation. The last bin shows a clear favour towards the $C\mathcal{P}$ -even hypothesis.

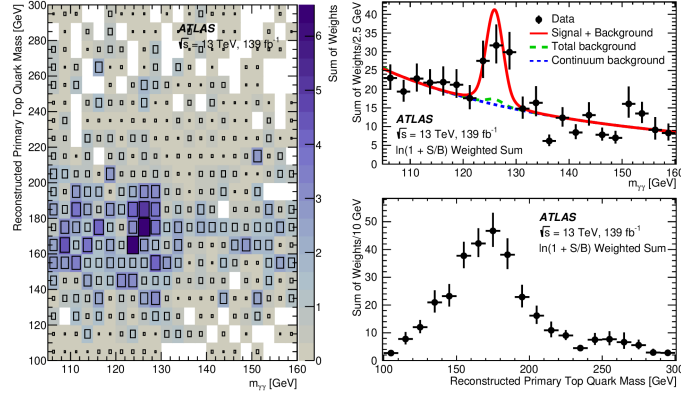


Figure 4: Distribution of reconstructed primary top mass versus Higgs mass in data events (left). Projection to both particle mass axes (right). Data error bars are statistical. The events are weighted by $\ln(1 + S/B)$ with S and B being the fitted signal and background yields in the smallest $m_{\gamma\gamma}$ interval containing 90% of the signal in each category. Figure from Ref. [3]

3.1 $t\bar{t}H$ signal strength

Assuming a $C\mathcal{P}$ -even coupling, and constraining all non- $t\bar{t}H$ Higgs Boson processes to their SM predictions, the measured rate for $t\bar{t}H$ is $\mu_{t\bar{t}H} = 1.43^{+0.33}_{-0.31}(\text{stat}) +^{+0.21}_{-0.15}(\text{syst})$ times the SM expectation. The background-only hypothesis is rejected with an observed (expected) significance of 5.2σ (4.4σ).

3.2 tH cross-section upper limit

Under the same assumptions, the used CLs method [12] yields a 95% confidence level (CL) upper limit of 12 times the SM prediction for tH production cross-section, the same as expected assuming the presence of SM tH signal.

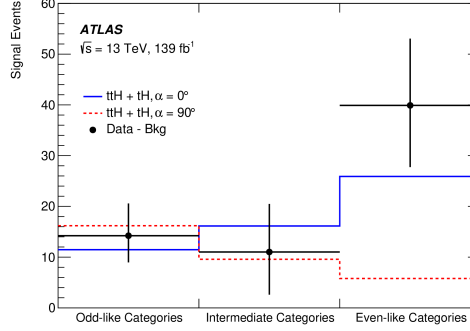


Figure 5: Data comparison with $C\mathcal{P}$ -even and $C\mathcal{P}$ -odd hypothesis. SM $C\mathcal{P}$ -even coupling is favoured. Figure from Ref. [3].

3.3 Limits on $C\mathcal{P}$ -mixing angle α

From the fit, the 1D (mixing angle α) and 2D ($\kappa_t \cos \alpha - \kappa_t \sin \alpha$ contours) limits on the $C\mathcal{P}$ properties of the top-Yukawa coupling can be extracted. These are shown in Figure 6 in the left and right panels respectively.

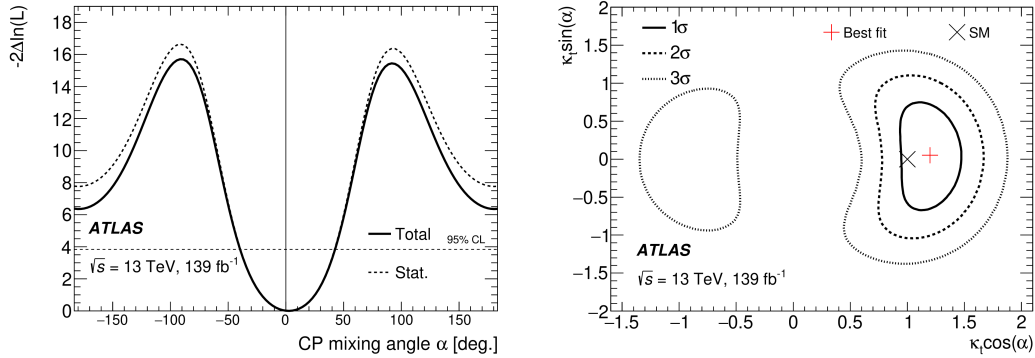


Figure 6: One-dimensional likelihood distribution of the mixing angle α (left), and 2D two-dimensional $\kappa_t \cos \alpha - \kappa_t \sin \alpha$ likelihood contours (right) results for $C\mathcal{P}$ limit. Figures from Ref. [3].

Additional information about the top-Yukawa coupling is required. The corresponding Higgs boson coupling modifiers κ_γ and κ_g are taken from the Run 2 Higgs boson coupling combination [13] (without including the $t\bar{t}H$ process). With these, the expected (observed) exclusion limit on the mixing angle (without a prior constraint on κ_t) is $|\alpha| > 43(63)^\circ$ at 95% CL. The $C\mathcal{P}$ -odd hypothesis is excluded at 3.9σ (2.5σ). In this analysis, the statistical uncertainty is the dominant one. These results are documented in Ref. [3].

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