PROCEEDINGS OF SCIENCE

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

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These proceedings present the first search for $\mathcal{CP}$-violation in the top-Yukawa coupling using $t\bar{t}H$ and tH production modes in the diphoton decay channel ($H \to \gamma\gamma$). The analysis is based on the 139 fb^{-1} of proton-proton collision data at center-of-mass energy $\sqrt{s}$ = 13 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 $\mathcal{CP}$-even and $\mathcal{CP}$-odd signal hypotheses.

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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 ($\mathcal{CP}$) 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 ($J^{\mathcal{CP}} = 0^{++}$) with a prescribed coupling to the top quark. However, the presence of a $J^{\mathcal{CP}} = 0^{+-}$ pseudoscalar admixture, which introduces a second coupling to the top quark, has not yet been excluded. The observation of this $\mathcal{CP}$-odd contribution would be a sign of beyond the SM physics.

There are two main processes to explore the $\mathcal{CP}$ properties of the top-Yukawa coupling: the $t\bar{t}H$ and the tH production. The $\mathcal{CP}$-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 $H \to \gamma\gamma$ branching ratio and the ggF production.

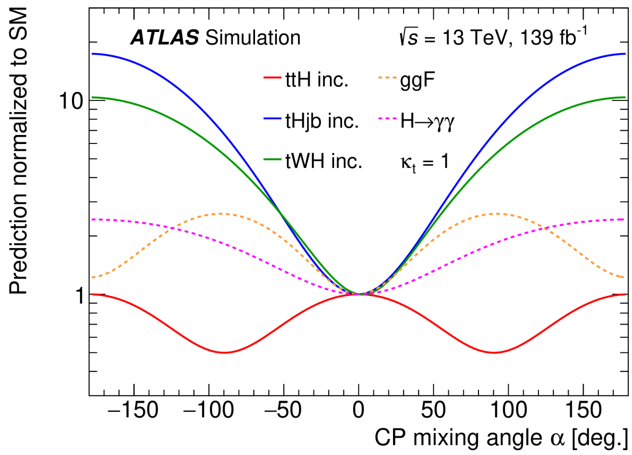

Figure 1: Dependence of the expected rates on the mixing angle for $\kappa_t = 1$. Normalised to the SM expectation. Figure from Ref. [3].

This analysis is performed using 139 fb^{-1} of $\sqrt{s} = 13$ 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 $\mathcal{CP}$-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

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

where m_t is the top quark mass, v is the Higgs vacuum expectation value, κ_t (> 0) is the top-Yukawa coupling parameter, and α is the $\mathcal{CP}$-mixing angle. The term proportional to $\sin\alpha$ introduces the $\mathcal{CP}$-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 identification 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 $p_{\mathrm{T}} > 25$ 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.

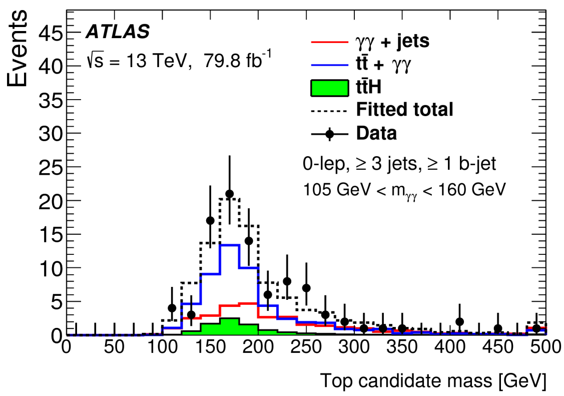

Figure 2: Distribution of the reconstructed top quark-candidate in the diphoton mass window from a triplet of jets selected by the dedicated "Top Reco BDT". There is a good agreement with data. Figure from Ref. [1].

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

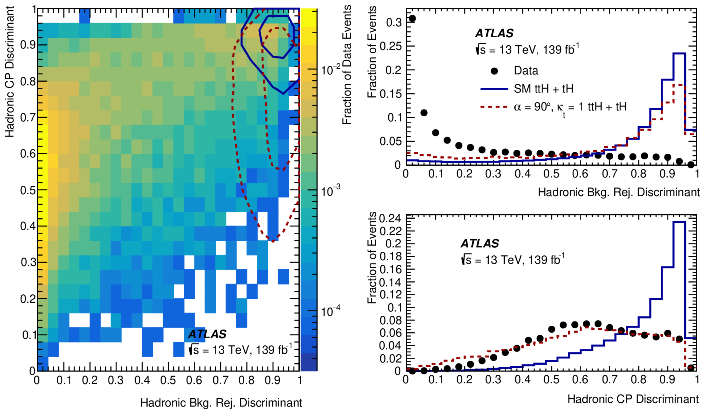

Figure 3: Two dimensional BDT distribution for the hadronic channel (left). Inner (outer) contours capture 25% (50%) of $t\bar{t}H$ and tH signal events. Projections to Background and CP BDT axes normalized to unity (right). Figure from Ref. [3].

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 $\mathcal{CP}$-even hypothesis.

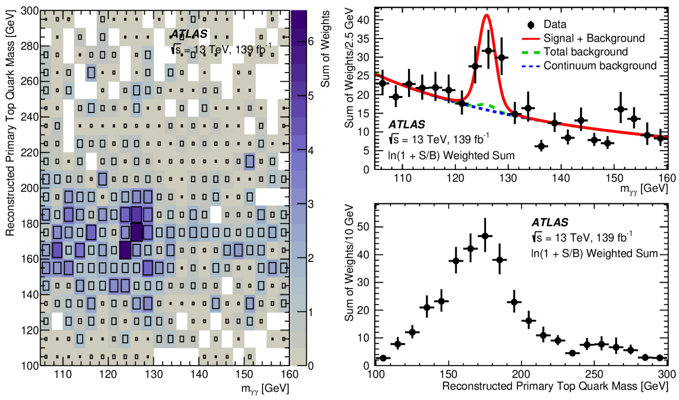

Figure 4: Distribution of reconstructed primary top mass versus Higgs mass in data events (left). Projection to both particle mass axes (right). Data error bars are statistical. The events are weighted by $\ln(1 + S/B)$ with S and B being the fitted signal and background yields in the smallest $m_{\gamma\gamma}$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

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

Assuming a $\mathcal{CP}$-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 $\mu_{t\bar{t}H} = 1.43^{+0.33}_{-0.31}(\text{stat}) +^{+0.21}_{-0.15}$ (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.

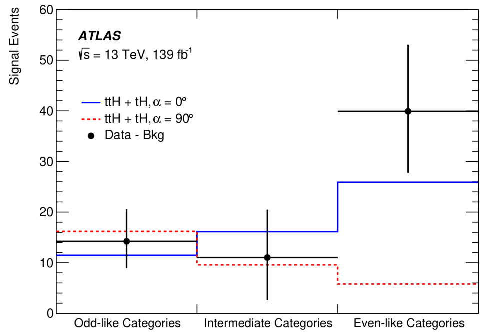

Figure 5: Data comparison with $\mathcal{CP}$-even and $\mathcal{CP}$-odd hypothesis. SM $\mathcal{CP}$-even coupling is favoured. Figure from Ref. [3].

3.3 Limits on $\mathcal{CP}$-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 $\mathcal{CP}$ properties of the top-Yukawa coupling can be extracted. These are shown in Figure 6 in the left and right panels respectively.

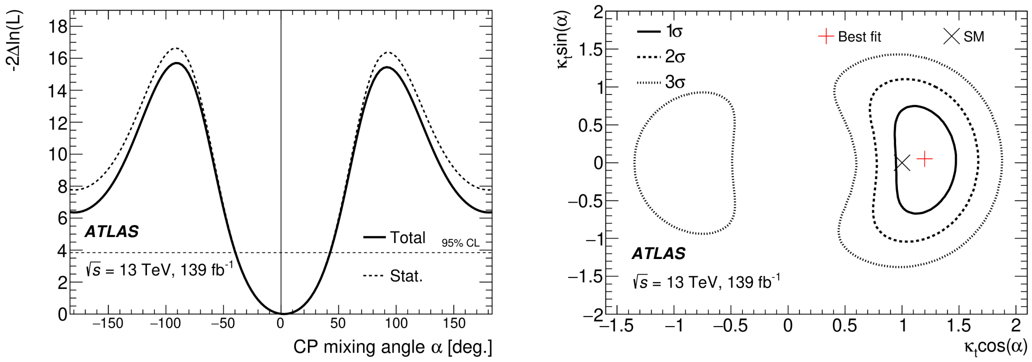

Figure 6: One-dimensional likelihood distribution of the mixing angle α (left), and 2D two-dimensional $\kappa_t \cos\alpha - \kappa_t \sin\alpha$ likelihood contours (right) results for $\mathcal{CP}$ limit. Figures from Ref. [3].

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 $\mathcal{CP}$-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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