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Between even and odd: probing the CP nature of the Higgs-top Yukawa coupling

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As we enter the era of precision at the LHC, excluding specific charge-parity (CP) scenarios is no longer enough: we want to detect and precisely measure the parameter that determines the possible admixture of CP-even and CP-odd components in the Higgs-top Yukawa coupling. Higgs boson production in association with top-quarks ($t\bar{t}H$ and tH), in the $H \to b\bar{b}$ decay channel, offers a unique possibility to study this interaction, since it depends only on Yukawa couplings and relies on the tree-level couplings between the Higgs and the fermions. Targeting events where one or both top quarks decay leptonically provides a handle to reconstruct the top-quarks, whose four-momenta can be used to construct CP-sensitive observables. In these proceedings, the first measurement of the CP-mixing angle in the $t\bar{t}H(H \to b\bar{b})$ channel using the full Run-2 dataset collected by the ATLAS experiment will be presented.

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1. Introduction and theoretical framework

Since the discovery of the Higgs boson by the ATLAS [1] and CMS collaborations [2], its properties have been scrutinized in increasingly more detail. The observation the Higgs boson associated production with top-quarks ($t\bar{t}H$) provides a direct experimental probe of the top Yukawa coupling at tree-level. As the dataset delivered by the LHC and collected by the experiments reaches unprecedentedly high integrated luminosity, the study of the charge-parity (CP) properties of the Higgs-top coupling becomes a possibility. This contribution presents the first measurement of the CP properties of the top Yukawa coupling using the $t\bar{t}H$ and tH production modes, in the $H \to b\bar{b}$ channel.

The Standard Model (SM) predicts the Higgs boson to be a scalar CP-even particle ($J^{CP} = 0^{++}$). A pure CP-odd coupling has been ruled out experimentally in the interaction with vector bosons and analyses of associated production with top quarks in the $H \to \gamma\gamma$ channel have excluded a pure CP-odd coupling at more than 3σ significance [3]. However, an admixture of CP-even and CP-odd states has not yet been ruled out and is worth investigating, since its observation would be a clear sign of physics beyond the SM, opening up the possibility of CP-violation in the Higgs sector. Such a new source of CP-violation could play a fundamental role in explaining the matter-antimatter asymmetry of the Universe.

The top-Higgs interaction can be extended beyond the SM as:

$$\mathcal{L}_{t\bar{t}H} = -k_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t \,, \tag{1}$$

where y_t is the SM Yukawa coupling strength, modified by a coupling modifier k_t', α is the CP-mixing angle, ϕ is the Higgs field, ψ_t and $\bar{\psi}_t$ are top-quark spinor fields and γ_5 is a Dirac matrix. A pure CP-even coupling corresponds to $\alpha = 0°$ while $\alpha = 90°$ indicates a pure CP-odd coupling.

2. Signal and background modeling

Event pre-selection consists of requirements on the number of jets and b-jets, after which $t\bar{t}$ production with additional heavy flavor jets (b and c-jets) constitutes the dominant background. Other processes contribute less than 10% to the total expected background. All background processes are modeled using Monte Carlo simulation (MC), following the strategy of the previously published Simplified Template Cross-Section measurement (STXS) in the same channel [4], and therefore will not be described here.

The signal processes, $t\bar{t}H$ and tH, are simulated for different values of α and k_t' using MadGraph5_aMC@NLO. The non-SM scenarios are simulated using the NLO Higgs Characterization model implemented in FeynRules.

For $t\bar{t}H$, the cross-section is normalized to 507 fb from the fixed order calculation at NLO in QCD and with electroweak corrections. For tH, two sub-processes are considered: $tHjb$ and tWH. The SM cross-sections are 60.1 fb and 16.7 fb, respectively, and are obtained from MadGraph5_aMC@NLO.

The signal yields are parameterized based on the simulated yields of $t\bar{t}H$ and tH for different values of α and k_t', in each analysis bin, in order to provide a smooth prediction of the signal yield in the range of explored values of the parameters of interest. The $t\bar{t}H$ yield is parameterized as $k_t' \cos(\alpha) N_{\text{CP-even}} + k_t' \sin(\alpha) N_{\text{CP-odd}}$, where $N_{\text{CP-even}}$ and $N_{\text{CP-odd}}$ are the predicted SM and pure CP-odd yields. This was verified to be a good approximation using a maximal mixing sample ($\alpha = 45°$). The tH yield is parameterized as $[Ak_t'^2 \cos^2(\alpha) + Bk_t'^2 \sin^2(\alpha) + Ck_t' \cos(\alpha) + Dk_t' \sin(\alpha) + Ek_t'^2 \cos(\alpha)\sin(\alpha) + F] N_{\text{CP-even}}$, where the coefficients $A - F$ are obtained by fitting this expression to a set of 11 samples generated with different values of α and k_t'.

3. Analysis strategy

The analysis targets leptonic decays of the $t\bar{t}$ pair and the Higgs boson decay to a pair of b-quarks. It uses the full Run-2 proton-proton collision dataset collected by the ATLAS experiment, corresponding to a total integrated luminosity of 139 fb^{-1}. Events are required to have exactly one lepton (semileptonic channel) or exactly two leptons with opposite electric charge (dileptonic channel).

Events are firstly categorized based on the number of jets and b-tagged jets (b-jets) with different working points in order to define control regions and preliminary signal regions (PSR), summarized in Table 1. The latter are further subdivided based on the output of a multivariate algorithm trained to separate $t\bar{t}H$ signal from backgrounds, leading to the definition of additional control regions and the final signal regions (SRs), detailed in Table 2. The signal-to-background ratio for a pure CP-even(odd) signal is at least 8(5)% in the SRs.

Events containing Higgs boson candidates with a high transverse momentum ("boosted", $p_T > 300$ GeV) are also considered and assigned to a specific orthogonal category. The boosted Higgs candidates are reconstructed from large-radius jets and identified by a neural network.

The dominant background is $t\bar{t}$ production with additional heavy flavor jets, in particular b-jets ($t\bar{t}+ \geq 1b$). The CRs have different fractions of $t\bar{t}+$light, $t\bar{t}+ \geq 1c$ and $t\bar{t}+ \geq 1b$ and help constrain the systematic uncertainties associated with each background component.

In the SRs and in the CRs with highest signal purity, dedicated CP-sensitive angular observables are used as final discriminants: b_2 in the single-lepton regions with $\geq 6j, \geq 4b$ and b_4 in the $\geq 4j, \geq 4b$ dilepton regions. The distribution of the b_4 variable in the purest dilepton signal region is shown in Figure 3. In the dilepton channel, there are events for which the reconstruction of the $t\bar{t}$ pair is not possible, because the neutrino weighting technique used to reconstruct the neutrinos' momenta does not always provide a solution [5, 6]. These are assigned to a dedicated region, $CR^{\geq 4j, \geq 4b}_{\text{no-reco}}$, in which the difference in η between the two leptons, $\Delta\eta_{\ell\ell}$, that still provides some CP discrimination, is used instead. The b_2 and b_4 variables are defined as:

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \tag{2}$$

where $\vec{p}_i$ with $i = 1, 2$ are the momentum three-vector of the two top quarks in the events and $\hat{z}$ is a unit vector in the direction of the beamline and defines the z-axis. The b_4 observable exploits the enhanced production of top quarks travelling in opposite longitudinal directions and closer to the beamline in CP-odd $t\bar{t}H$ production. The observable b_2 relies simultaneously on the smaller azimuthal separation of top quarks and on their larger longitudinal fraction of momentum in CP-odd $t\bar{t}H$ production. To enhance the discrimination power, the calculation of b_2 is performed in the $t\bar{t}H$ rest frame.

Region		Dilepton				ℓ+jets			
		$\mathrm{PSR}^{\geq 4j,\geq 4b}$	$\mathrm{CR}_{\mathrm{hi}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{lo}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{hi}}^{3j,3b}$	$\mathrm{PSR}^{\geq 6j,\geq 4b}$	$\mathrm{CR}_{\mathrm{hi}}^{5j,\geq 4b}$	$\mathrm{CR}_{\mathrm{lo}}^{5j,\geq 4b}$	$\mathrm{PSR}_{\mathrm{boosted}}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b-\mathrm{tag}}$	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$		–				0			≥ 1

Figure 1: Definition of the CRs and PSRs according to the number of jets and b-tagged jets using different b-tagging working points, and the number of boosted Higgs boson candidates.

Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{PSR}^{\geq 4j,\geq 4b}$)	$\mathrm{CR}_{\text{no-reco}}^{\geq 4j,\geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j,\geq 4b}$	BDT$\in [-1, -0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j,\geq 4b}$	BDT$\in [-0.086, 0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j,\geq 4b}$	BDT$\in [0.186, 1]$	b_4
ℓ+jets ($\mathrm{PSR}^{\geq 6j,\geq 4b}$)	$\mathrm{CR}_1^{\geq 6j,\geq 4b}$	BDT$\in [-1, -0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j,\geq 4b}$	BDT$\in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j,\geq 4b}$	BDT$\in [0.249, 1]$	b_2
ℓ+jets ($\mathrm{PSR}_{\mathrm{boosted}}$)	$\mathrm{SR}_{\mathrm{boosted}}$	BDT$\in [-0.05, 1]$	Classification BDT score

Figure 2: Summary of the selections used to define SRs and CRs in the PSRs based on the classification BDT score.

4. Results

A binned profile likelihood fit is performed in all analysis regions simultaneously in order to extract the values of α and k_t'. The profile likelihood ratio is used as the test statistic. By scanning the value of the test statistic in grid points of the $\alpha - k_t'$ plane, two-dimensional exclusion contours are obtained, shown in Figure 4, where the best-fit point is marked with a dark blue star. The best-fit value of the CP-mixing angle α is $11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$ and the overall coupling strength k_t' is $0.83^{+0.30}_{-0.46}$. These values are in agreement with the SM expectation. The data disfavours the pure CP-odd hypothesis with 1.2σ significance. The significance of the observed $t\bar{t}H$ and tH signal over the background-only hypothesis is 1.3σ. The normalization of the $t\bar{t}+\geq 1b$ is controlled by a free-floating parameter and measured to be $1.30^{+0.09}_{-0.08}$.

The uncertainty in the measured value of α is dominated by $t\bar{t}+\geq 1b$ modeling uncertainties which contribute ${}^{+40^{\circ}}_{-55^{\circ}}$ to the total uncertainty. The main contributions to the modeling uncertainty come from the NLO matching procedure between the matrix element and the parton shower (PS), PS and hadronization, and choice of the flavour scheme, of which the latter is dominant.

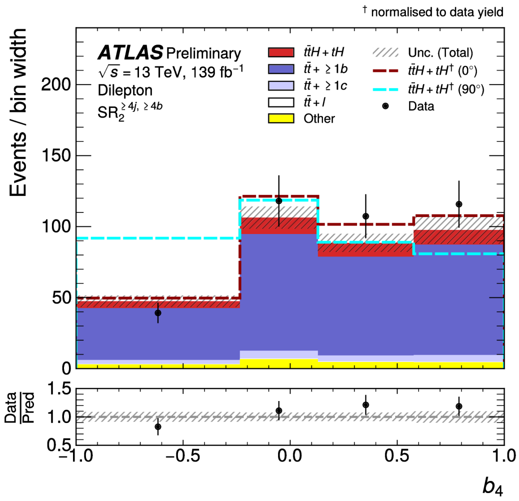

Figure 3: Distribution of the b_4 variable in the purest dilepton signal region [7].

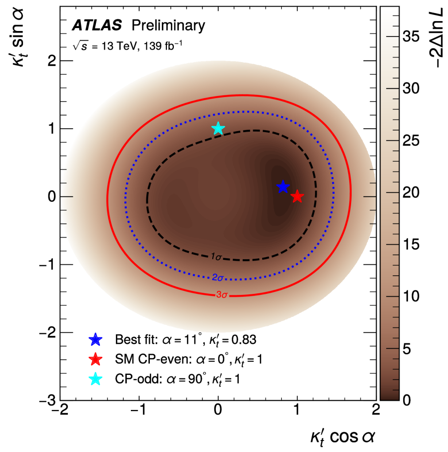

Figure 4: The observed exclusion contours in the $k_t' \cos(\alpha)$-$k_t' \sin(\alpha)$ plane in $t\bar{t}H \to b\bar{b}$ [7].

5. Conclusions

This contribution presents the first CP measurement performed in Higgs boson associated production with top-quarks in the $H \to b\bar{b}$ decay channel. Novel angular observables calculated between the top-quarks are employed as final discriminant variables. The measured values of the CP-mixing angle and overall coupling modifier are in agreement with the SM expectation. The measurement's sensitivity is highly limited by systematic uncertainties in the modelling of the dominant $t\bar{t}+\geq 1b$ background.

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