Study of CP properties of top-Higgs interaction in ttH/tH, H→γγ channel with ATLAS experiment

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Higgs potential and BSM opportunity

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Introduction

• Large matter-antimatter asymmetry in Universe cannot be explained by known CP violation mechanism in SM: looking for additional CP violation sources is well-motivated

• Study of CP properties in Higgs sector started with V-H interactions since the Higgs boson discovery in 2012

• CP properties of fermion Yukawa coupling, in particular the largest top Yukawa coupling, were not directly studied until Run 2
CP properties of top Yukawa coupling

- The Lagrangian for $t$-$H$ interaction including CP mixing is

$$\mathcal{L}_t = -\frac{m}{\nu}\kappa_t (\cos(\alpha)\bar{t}t + i \sin(\alpha)\bar{t}\gamma_5 t)H, \quad \kappa_t > 0, \quad \alpha \in [-\pi, \pi]$$

SM corresponds to $\alpha = 0, \kappa_t = 1$, full CP odd is $\alpha = 90^\circ$

- Only indirect constraints on CP mixing in $t$-$H$ interaction existed before $ttH$ observation
  - Stringent limits from EDMs ($e, n, ...$): $\kappa_t \sin(\alpha) < 10^{-3}$
  - Also from loop-induced $H \rightarrow \gamma\gamma$ and $ggF$ rates: $\kappa_t \sin(\alpha) < \sim 0.5$

- The $ttH/tH$ production mode opens a new possibility to probe CP mixing directly in the top Yukawa coupling at tree-level

- The $H \rightarrow \gamma\gamma$ channel is ideal for this study due to excellent sensitivity and clean signature
What if there is CP mixing?

- The presence of a CP odd component in t-H coupling alters:
  - Cross sections as well as kinematics of ttH & tH processes: provide **direct constraint** of CP mixing in top Yukawa coupling (focus of this analysis)
  - H→γγ BR and ggF cross-sections: indirect constraint, also sensitive to other new physics scenarios

\[ \begin{align*}
  \text{ttH} & \quad \text{tH} \\
  \text{ggF} & \quad \text{H→γγ}
\end{align*} \]

\[ \begin{align*}
  \text{Prediction normalized to SM} \quad \text{ATLAS Simulation} \\
  \gamma\gamma & \quad H \rightarrow \gamma\gamma
\end{align*} \]

PRL 125 (2020) 061802
Analysis strategy

- Divide diphoton sample into two regions
  - **Hadronic** (≥3 jets, ≥1 b-jet, 0 lep)
  - **Leptonic** (≥1 b-jet, ≥1 lep)

- In each region, train following two BDTs (using XGBoost package)
  - **Bkg. rejection BDT**: separate ttH-like events from continuum background
  - **CP BDT**: separate CP-even ttH/tH events from CP-odd

- Divide categories on 2D plane of bkg. rejection vs. CP BDTs

- Fit the $m_{\gamma\gamma}$ spectrum in all categories simultaneously to extract signal

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(PRL 125 (2020) 061802)
Background rejection BDT

• Use the same BDT discriminant (but not categories!) from \( \text{ttH search} \), which is trained using low-level inputs such as 4-vec. of \( \gamma, j, l, \) and MET

• Serves the purpose of CP analysis very well
  - Good rejection of background; good acceptance of ttH/tH signal
  - Weak dependence on CP mixing angle

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\( \text{PRL 125 (2020) 061802} \)
CP sensitive observables

- Compared with SM (CP even), CP odd $ttH/tH$ gives
  - Larger $m_{tH}$ and $m_{tt}$; more boosted $p_T(H)$
  - Less back-to-back $\phi(tt)$; larger opening $\eta(tt)$

- Exploit shape information in this analysis. Avoid relying on normalization dependence
• Train **top reconstruction BDT** to reconstruct two top quarks $t_1, t_2$
  - Trained using ttH sample: correct pairing vs. wrong paring
  - In case $t_2$ cannot be built, sum up all remaining objects as $t_2$
• Train **CP BDT** to separate between **CP even** and **CP odd** ttH+tH
  - $p_T/\eta$ of diphoton system; $H_T, n_{\text{jets}}, n_{\text{bjets}}, \Delta R(\gamma, j)$
  - $p_T/\eta/\phi$ / **top reco. BDT** score of $t_1$ and $t_2$, $m_{t_1H}, m_{t_1t_2}, \phi(t_1t_2), \eta(t_1t_2)$

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**ATLAS**

$\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$

0-lep, $\geq 3$ jets, $\geq 1$ b-jet
$105$ GeV $< m_{\gamma\gamma} < 160$ GeV

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Categorization

- Scan category boundaries on 2D bkg. rejection BDT vs. CP BDT plane to optimize both SM ttH significance and CP separation
- 20 analysis categories defined in total
  - 12 categories in hadronic region, 8 in leptonic

**Signal yields**

**CP even**
- ttH/tH

**Hadronic**
- ggF
- VBF
- VH
- ttH $\alpha = 0^\circ$
- tH $\alpha = 0^\circ$
- tWH $\alpha = 0^\circ$

**Leptonic**

**ATLAS**
- $\sqrt{s} = 13$ TeV
- 139 fb$^{-1}$
- $\kappa_1 = 1$

**Expected event yield**

**Signal yields**

**CP odd**
- ttH/tH

**Hadronic**
- ggF
- VBF
- VH
- ttH $\alpha = 90^\circ$
- tH $\alpha = 90^\circ$
- tWH $\alpha = 90^\circ$

**Leptonic**

**ATLAS**
- $\sqrt{s} = 13$ TeV
- 139 fb$^{-1}$
- $\kappa_1 = 1$

**Expected event yield**

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ttH signal yield parameterization

- Parameterize ttH and tH signal yields in each category as mixing angle $\alpha$ and top Yukawa coupling strength $\kappa_t$
- For ttH process, use

$$A\kappa_t^2 \cos^2(\alpha) + B\kappa_t^2 \sin^2(\alpha) + E\kappa_t^2 \sin(\alpha)\cos(\alpha)$$

- Parameterization describe MC predictions well in all categories
- Coefficient E for interference term found to be negligible as expected

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tH signal yield parameterization

- For tHW and tHjb processes, need to use more complicated parameterizations considering interference between t-H and W-H

\[ A\kappa_t^2 \cos^2(\alpha) + B\kappa_t^2 \sin^2(\alpha) + C\kappa_t \cos(\alpha) + D\kappa_t \sin(\alpha) + E\kappa_t^2 \sin(\alpha)\cos(\alpha) + F \]

\[ a^2 \quad a'^2 \quad 2 \text{ Re}(a \ b) \quad 2 \text{ Re}(a' \ b) \quad 2\text{Re}(a \ a') \quad b^2 \]

Interference terms between CP even and odd found negligible

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**ATLAS Simulation**
\( \bar{\sigma} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
Inclusive, \( \chi^2 \) p-value = 63.7 %

Acos(\alpha) + Bsin(\alpha) + Cos(\alpha) + Dsin(\alpha) + Esin(\alpha)\cos(\alpha) + F

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ttH and tH cross-section measurements

- Single-channel ttH observation at $5.2\sigma$, assuming SM for other prod. modes

$$\mu = 1.43^{+0.33}_{-0.31} \text{(stat.)} +0.21_{-0.15} \text{(syst.)}$$

- tH cross-section < $12 \times \text{SM @95\% CL}$
• Provide **direct** constrain mixing angle $\alpha$ using only $ttH$ and $tH$ info
  
  - Use $\kappa_\gamma$ vs $\kappa_g$ contour ($80 \text{ fb}^{-1}$) to constrain $H \rightarrow \gamma \gamma$ and ggF rates

• $|\alpha| > 43^\circ$ excluded @95% CL **without** assumption on $\kappa_t$

- **PRL 125 (2020) 061802**
CP constraint: resolve $H \rightarrow \gamma\gamma/ggF$ loops

- Assume potential new physics in $H \rightarrow \gamma\gamma/ggF$ is only in t-H coupling, and can be parameterized as function of $\alpha$ and $\kappa_t$ (Ellis et. al. JHEP 04 (2014) 004)

\[
\kappa_g^2 = \kappa_t^2 \cos^2(\alpha) + 2.6\kappa_t^2 \sin^2(\alpha) + 0.11\kappa_t \cos(\alpha)(\kappa_t \cos(\alpha) - 1)
\]
\[
\kappa_\gamma^2 = (1.28 - 0.28\kappa_t \cos(\alpha))^2 + (0.43\kappa_t \sin(\alpha))^2
\]

- Exclude $|\alpha| > 43^\circ$ @95% CL without assumption on $\kappa_t$

Using only ttH and tH info

PRL 125 (2020) 061802
Conclusions

• CP properties of top Yukawa coupling studied with ATLAS experiment based on full Run 2 data
  - CMS results: *PRL* **125** (2020) **061801**
  - No deviation from SM observed yet
  - Constraint limited by statistical uncertainty

• In the meantime, explore other Higgs decay channels (e.g. $H\rightarrow bb$ and multi-lepton), SM top processes (e.g. 4-top production *PRD* **99** (2019) **113003**), and Higgs combination (using ggF and $H\rightarrow \gamma\gamma$ rates + ttH rate & kinematics)
SM Higgs boson production at LHC

Main

- Distinct topology from each production mode
- Cross section of main production modes calculated with relatively high accuracy
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios

<table>
<thead>
<tr>
<th>Production Mode</th>
<th>Cross Section</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon-fusion ggF</td>
<td>~87%</td>
<td><img src="ggF.png" alt="Gluon-fusion ggF" /></td>
</tr>
<tr>
<td>Vector boson fusion (VBF)</td>
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</tr>
<tr>
<td>VH</td>
<td>~4%</td>
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</tr>
<tr>
<td>ttH</td>
<td>~1%</td>
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Gluon-fusion ggF (~87%)

Vector boson fusion (VBF) (~7%)

VH (~4%)

ttH (~1%)

Rare

- bbH (~1%) 0.49 pb
- tH (~0.1%) 0.09 pb
Higgs boson decays

- "Big five": $\gamma\gamma$ (0.23%), ZZ, WW, $\tau\tau$, bb
- "Rare" channels: $\mu\mu$ (0.022%), $Z\gamma$, cc, etc.

$$
H \rightarrow ff, \quad H \rightarrow VV, \quad H \rightarrow \gamma\gamma/Z\gamma
$$
The ATLAS detector

Run 1

Higgs boson discovery ★

Run 2

13 TeV

splice consolidation button collimators R2E project


75% nominal Lumi

30 fb⁻¹

8 TeV

Run 3

13 - 14 TeV

Diodes Consolidation LIU Installation

Civil Eng. P1-P5

2019 2020 2021 2022 2023 2024 2025 2026 2027 2040

3000 fb⁻¹

4000 fb⁻¹

We are here

Run 4 - 5...

14 TeV

HL-LHC installation

HLC CIVIL ENGINEERING:

HL-LHC TECHNICAL EQUIPMENT:

ALICE - LHCb upgrade

ATLAS - CMS HL-LHC

experiment beam pipes

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

190 fb⁻¹

Hongtao Yang (LBNL)

Aug 27, 2021, Higgs potential and BSM opportunity
• **139 fb\(^{-1}\) of 13 TeV** proton-proton collision data collected for physics by ATLAS detector
  - Average 34 interactions per bunch crossing
• Thanks to the excellent LHC performance and smooth operation of ATLAS detector
Data & signal MC samples for ttH CP analysis

- **Data**: full Run 2 dataset of 139 fb$^{-1}$

- **ttH/tH signal**: NLO MG5_aMC+Pythia8 using Higgs Characterization (HC) model
  - ttH: $\kappa_t = 1$, $\alpha = 0^\circ, 15^\circ, 30^\circ, \ldots, 90^\circ$
  - tHjb/tWH: sample generated with both $\kappa_t = 1$ and $\neq 1$ at different mixing angles. $\kappa_W = 1$

- **ggF signal**: PowHeg NNLOPS
  - Kinematic dependence on CP mixing checked to be well-covered by syst. using MG_aMC HC model ggF+2j samples

- **Other Higgs production modes**: same as typical ATLAS Run 2 Higgs analyses