Probing the Anomalous Top-Yukawa Coupling at the LHC

Chih-Ting Lu (NTHU)
National Tsing Hua University, Hsinchu, Taiwan
Collaborators for this work:

- Prof. Kingman Cheung
- Prof. Jae Sik Lee
- Dr. Jung Chang

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Outline

1. Motivation

2. Highlight some experimental results for the Higgs boson at the LHC

3. Formalism and Results from Higgs Precision (Higgcision) analysis

4. Entangling Higgs production associated with a single top and a top-pair in the presence of anomalous top-Yukawa coupling

5. Conclusions
Motivation

- Why is it important for the discovery of the Higgs boson?

- 1. It is a byproduct of the BEH mechanism, so if we discover the Higgs boson, then we can confirm the BEH mechanism! (It is NOT just a new scalar particle!)

- 2. New type of interactions:

\[
\begin{align*}
W, Z & \quad = \quad gM_W, \quad \frac{gM_Z}{\cos \theta_W} \\
W, Z & \quad = \quad gM_f, \quad \frac{gM_f}{2M_W}
\end{align*}
\]
Highlight some experimental results for the Higgs boson at the LHC

\[
\frac{\sigma_{ttH}/\sigma_{ggF}}{\text{the same ratio in SM}} = 3.3 \pm 0.9
\]

\[
\frac{\sigma_{ZH}/\sigma_{ggF}}{\text{the same ratio in SM}} = 3.2 \pm 1.4
\]

\[
\frac{B^{bb}/B^{ZZ}}{\text{the same ratio in SM}} = 0.19 \pm 0.21
\]
Highlight some experimental results for the Higgs boson at the LHC

arXiv:1606.02266
Highlight some experimental results for the Higgs boson at the LHC
Highlight some experimental results for the Higgs boson at the LHC

**ttH production**

Important to study directly the coupling of top to Higgs

Looking for final states with H decay to ZZ,WW and $\tau\tau$ (yielding events with 2-3 leptons).

$\mu = 2.0^{+0.8}_{-0.7}$ within statistics, compatible with SM
Highlight some experimental results for the Higgs boson at the LHC.
Assuming that the Higgs boson $h$ is a generic CP-mixed state, we can write the gauge-Higgs and Yukawa coupling as

$$\mathcal{L}_{hVV} = g m_W \left( g_{hWW} W^+ W^- + g_{hZZ} \frac{1}{2 c_W^2} Z Z^\mu \right) h,$$

$$\mathcal{L}_{hff} = - \sum_{f=t,b,c,\tau} \frac{g m_f}{2 m_W} \bar{f} \left( g_{hff}^S + i g_{hff}^P \gamma_5 \right) f h.$$
The amplitude for the decay process $h \rightarrow \gamma \gamma$ can be written as

$$M_{h\gamma\gamma} = -\frac{\alpha m_h^2}{4\pi v} \left\{ S^\gamma(m_h) \left( \epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^* \right) - P^\gamma(m_h) \frac{2}{m_h^2} \langle \epsilon_{1\perp}^* \epsilon_{2\perp}^* k_1 k_2 \rangle \right\},$$

where $k_{1,2}$ are the momenta of the two photons and $\epsilon_{1,2}$ the wave vectors of the corresponding photons, $\epsilon_{1\perp}^\mu = \epsilon_{1\perp}^\mu - 2k_1^\mu(k_1 \cdot \epsilon_1)/m_1^2$, $\epsilon_{2\perp}^\mu = \epsilon_{2\perp}^\mu - 2k_2^\mu(k_2 \cdot \epsilon_2)/m_2^2$ and $\langle \epsilon_1 \epsilon_2 k_1 k_2 \rangle \equiv \epsilon_{\mu\nu\rho\sigma}^1 \epsilon_{2\mu}^\nu \epsilon_{k_1\rho}^\nu \epsilon_{k_2\sigma}^\nu$. Retaining only the dominant loop contributions from the third-generation fermions and $W^\pm$, and including some additional loop contributions from new particles, the scalar and pseudoscalar form factors are given by

$$S^\gamma(m_h) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{hff}^S F_{sf}(\tau_f) - g_{hWW} F_1(\tau_W) + \Delta S^\gamma,$$

$$P^\gamma(m_h) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{hff}^P F_{pf}(\tau_f) + \Delta P^\gamma,$$

where $\tau_x = m_h^2/4m_x^2$, $N_C = 3$ for quarks and $N_C = 1$ for tau leptons, respectively.

In the SM, $P^\gamma = 0$, $g_{hff}^S = g_{hWW} = 1$ and $\Delta S^\gamma = 0$. 
Formalism from Higgs Precision (Higgcision) analysis

Similarly, the amplitude for the decay process $h \rightarrow gg$ can be written as

$$\mathcal{M}_{Hgg} = -\frac{\alpha_s m_h^2 \delta^{ab}}{4\pi v} \left\{ S^g(m_h) (\varepsilon^*_1 \cdot \varepsilon^*_2) - P^g(m_h) \frac{2}{m_h^2} \langle \varepsilon^*_1 \varepsilon^*_2 k_1 k_2 \rangle \right\},$$

where $a$ and $b$ ($a, b = 1$ to 8) are indices of the eight $SU(3)$ generators in the adjoint representation. Including some additional loop contributions from new particles, the scalar and pseudoscalar form factors are given by

$$S^g(m_h) = \sum_{f=b,t} g^S_{hff} F_{sf}(\tau_f) + \Delta S^g,$$

$$P^g(m_h) = \sum_{f=b,t} g^P_{hff} F_{pf}(\tau_f) + \Delta P^g. \quad (6)$$

In the SM, $P^g = 0$, $g^S_{hff} = 1$ and $\Delta S^g = 0$. 
Formalism from Higgs Precision (Higgcision) analysis

- Since we are primarily interested in size of the gauge-Higgs and top-Yukawa couplings and the relative sign between them, for bookkeeping purpose, we use the following simplified notations

\[
C_v \equiv g_{hWW} = g_{hZZ}, \quad C_t^{S,P} \equiv g_{htt}^{S,P}, \quad C_b^{S,P} \equiv g_{hbb}^{S,P}.
\]
Results from Higgs Precision (Higgscision) analysis for Run-I data

FIG. 2. The confidence-level regions in the plane of \((C_u^S, C_v)\) of the CPC4 fit by varying \(C_u^S, C_d^S, C_t^S\), and \(C_v\) while keeping \(\Delta S^d = \Delta S^u = \Delta \Gamma_{\text{tot}} = 0\). The contour regions shown are for \(\Delta \chi^2 \leq 2.3\) (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to confidence levels of 68.3%, 95%, and 99.7%, respectively. The best-fit point is denoted by the triangle.
Results from Higgs Precision (Higgscision) analysis for Run-I data

FIG. 3. The confidence-level regions in the plane of \((C_u^3, C_v^1), (C_u^2, \Delta S^v), (C_u^3, \Delta S^v)\) of the CP conserving fit by varying \(C_d^3, C_d^1, C_f^3, C_v, \Delta S^v, \Delta S^v\). The contour regions shown are for \(\Delta \chi^2 \leq 2.3\) (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to confidence levels of 68.3%, 95%, and 99.7%, respectively. The best-fit points are denoted by the triangles.
As shown in Refs. [3] in which the model-independent fit to the current Higgs data is performed, the negative $C_t^S = -1$ is ruled at 95%CL if only the gauge-Higgs coupling $C_v$ and the top-Yukawa coupling $C_t^S$ vary. However, $C_t^S = -1$ is still allowed at 95%CL when the gauge-Higgs $C_v$, top-Yukawa $C_t^S$, bottom-Yukawa $C_b^S$, and tau-Yukawa $C_\tau^S$ couplings are all allowed to vary. Furthermore, if some sizable contributions to $\Delta S^g$ and $\Delta S^g$ due to additional new particles running in the loop are assumed, a broad range of $C_t^S$ between $-2$ and $+2$ is still consistent with the current Higgs data.
Results from Higgs Precision (Higgscision) analysis for Run-I data

FIG. 4. The confidence-level regions of the fit by varying the scalar Yukawa couplings $C_u^S$ and $C_u^P$, and the pseudoscalar Yukawa couplings $C_u^P$, while keeping others at the SM values. The description of contour regions is the same as in Fig. 2.
Entangling Higgs production associated with a single top and a top-pair in the presence of anomalous top-Yukawa coupling
ttH production mode in Run-I data

It is strange …
ttH production mode in Run-I data

It is strange …
ttH production mode in Run-I data

It is strange ...

<table>
<thead>
<tr>
<th>Category</th>
<th>CMS $t\bar{t}h$ channel $\mu_{t\bar{t}h}^{\text{CMS}}$</th>
<th>ATLAS $t\bar{t}h$ channel $\mu_{t\bar{t}h}^{\text{ATLAS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$+2.7^{+2.6}_{-1.8}$</td>
<td>$+1.3^{+3.3}_{-2.1}$</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$+0.7^{+1.9}_{-1.9}$</td>
<td>$+1.5^{+1.1}_{-1.1}$</td>
</tr>
<tr>
<td>$\tau_{h}\tau_{h}$</td>
<td>$-1.3^{+6.3}_{-5.5}$</td>
<td>-</td>
</tr>
<tr>
<td>$2\ell 1\tau_{h}$</td>
<td>-</td>
<td>$-0.9^{+3.1}_{-2.0}$</td>
</tr>
<tr>
<td>$1\ell 2\tau_{h}$</td>
<td>-</td>
<td>$-9.6^{+9.6}_{-9.7}$</td>
</tr>
<tr>
<td>$4\ell$</td>
<td>$-4.7^{+5.0}_{-1.3}$</td>
<td>$+1.8^{+6.9}_{-2.0}$</td>
</tr>
<tr>
<td>$3\ell$</td>
<td>$+3.1^{+2.4}_{-1.2}$</td>
<td>$+2.8^{+2.2}_{-1.8}$</td>
</tr>
<tr>
<td>$ss2\ell$</td>
<td>$+5.3^{+2.1}_{-1.8}$</td>
<td>$+2.8^{+2.1}_{-1.9}$</td>
</tr>
</tbody>
</table>

TABLE I. The best-fit values for the category-dependent signal strengths $\mu_{t\bar{t}h}^{\text{CMS}}$ and $\mu_{t\bar{t}h}^{\text{ATLAS}}$ coming from the CMS [7] and ATLAS [10][14][15] searches, respectively, for the associated production of the Higgs boson with a top quark pair at $\sqrt{s} = 7$ and 8 TeV for $m_h = 125.6$ GeV (CMS) / 125 GeV (ATLAS).
Our Strategy

- In this work, we attempt to interpret the excess by exploiting the strong entanglement between the associated Higgs production with a single top quark (thX) and tth production in the presence of anomalous top-Yukawa coupling.

- As well known, tth production only depends on the absolute value of the top-Yukawa coupling.

- Meanwhile, in thX production, this degeneracy is lifted through the strong interference between the two main contributions which are proportional to the top-Yukawa and the gauge-Higgs couplings, respectively.

- Especially, when the relative sign of the top-Yukawa coupling with respect to the gauge-Higgs coupling is reversed, the thX cross section can be enhanced by more than one order of magnitude.
**tth production at LO**

FIG. 1. Feynman diagrams contributing to $tth$ production at LO.
thX production with X=j

FIG. 2. Feynman diagrams contributing to thX production with X = j.
thX production with $X = jb$

FIG. 3. Feynman diagrams contributing $thX$ production with $X = jb$. 
thX production with $X=W$
Variation of cross sections for thX production

Figure 5. Variation of the total cross sections versus $C_t^S$ for $pp \rightarrow thX$ with $X = j, jb, W, b$ in the order of the size of cross sections at (a) LHC-8 and (b) LHC-14. We have taken $C_v = C_b^S = 1$ and $C_t^{P,b} = 0$. No cuts are imposed except for the second process $pp \rightarrow thjb$ in which we applied the cuts in eq. (3.1) to remove the divergence.

<table>
<thead>
<tr>
<th>$C_t^S$</th>
<th>$X = j$</th>
<th>$X = j + b$</th>
<th>$X = W$</th>
<th>$X = b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_t^S = +1$</td>
<td>79.4 (17.1)</td>
<td>27.1 (5.95)</td>
<td>17.0 (2.89)</td>
<td>2.32 (0.833)</td>
</tr>
<tr>
<td>$C_t^S = 0$</td>
<td>305 (71.4)</td>
<td>90.0 (19.8)</td>
<td>34.4 (4.66)</td>
<td>0.368 (0.126)</td>
</tr>
<tr>
<td>$C_t^S = -1$</td>
<td>1030 (249)</td>
<td>325 (72.8)</td>
<td>146 (19.8)</td>
<td>1.52 (0.536)</td>
</tr>
</tbody>
</table>

Table 1. The leading-order production cross sections in fb for the processes $pp \rightarrow th + X$ at 14 TeV (8 TeV) LHC, taking $C_v = C_b^S = 1$ and $C_t^{P,b} = 0$. We have not applied any cuts except for the case with $X = j + b$ for which we required $p_{Tb} > 25$ GeV; $|\eta_b| < 2.5$; $p_{Tj} > 10$ GeV; $|\eta_j| < 5$; see text for details.
Variation of cross sections for thX production versus C^P_t

Figure 6. Production cross sections at the LHC-14 for pp → thj versus $\phi = \arctan(C_t^P/C_t^S)$ under the constraint $(C_t^S/0.86)^2 + (C_t^P/0.56)^2 = 1$. We take $C_\phi = 1$. The shaded regions are those disallowed at 68% C.L. by the Higgs data obtained in ref. [3].
Signal Strength

First we note that signal strengths depend on the decay modes of the top quark and the Higgs boson, as well as their production mechanisms. For a choice of experimentally-defined decay mode $\mathcal{D}$, and taking into account the $thX$ production processes, we define the signal strength $\mu(t\bar{t}h)$ with respect to the SM $t\bar{t}h$ production as follows

$$\mu(t\bar{t}h) = \frac{\eta_1 \sigma(t\bar{t}h) B(t\bar{t}h \to \mathcal{D}) + \sum_{X=j,b,W} \eta_X \sigma(thX) B(thX \to \mathcal{D})}{\eta_1^{SM} \sigma(t\bar{t}h)_{SM} B(t\bar{t}h \to \mathcal{D})_{SM}}, \quad (8)$$

where $\sigma(t\bar{t}h) = \sigma(pp \to t\bar{t}h)$ and $\sigma(thX) = \sigma(pp \to thX) + \sigma(pp \to t\bar{t}hX)$ are understood.
Signal Strength

The detection efficiencies $\eta$'s depend on the experimental apparatuses and cuts for the specific production and decay mode. By introducing the cross-section ratios

\[
R(t\bar{t}h) \equiv \frac{\sigma(t\bar{t}h)}{\sigma(t\bar{t}h)_{\text{SM}}}, \quad R(thj) \equiv \frac{\sigma(thj)}{\sigma(t\bar{t}h)_{\text{SM}}},
\]

\[
R(thjb) = \frac{\sigma(thjb)}{\sigma(t\bar{t}h)_{\text{SM}}}, \quad R(thW) = \frac{\sigma(thW)}{\sigma(t\bar{t}h)_{\text{SM}}},
\]

and the $D$-dependent detection-efficiency ratios

\[
\epsilon_1 = \frac{\eta_1B(t\bar{t}h \to D)}{\eta_1^{\text{SM}}B(t\bar{t}h \to D)_{\text{SM}}}, \quad \epsilon_2 = \frac{\eta_2B(thj \to D)}{\eta_2^{\text{SM}}B(t\bar{t}h \to D)_{\text{SM}}},
\]

\[
\epsilon_3 = \frac{\eta_3B(thjb \to D)}{\eta_3^{\text{SM}}B(t\bar{t}h \to D)_{\text{SM}}}, \quad \epsilon_4 = \frac{\eta_4B(thW \to D)}{\eta_4^{\text{SM}}B(t\bar{t}h \to D)_{\text{SM}}},
\]

one may have

\[
\mu(t\bar{t}h) = \epsilon_1 R(t\bar{t}h) + \epsilon_2 R(thj) + \epsilon_3 R(thjb) + \epsilon_4 R(thW).
\]

We note that $\epsilon_1 = R(t\bar{t}h) = 1$ in the SM limit of $C_v = 1$, $C_v^S = +1$, and $C_v^P = 0$ and $\mu(t\bar{t}h)$ is always larger than 1 due to the entanglement of $thX$ production. Our main task is to calculate the cross section ratios $R$'s in the presence of anomalous top-Yukawa coupling and the detection-efficiency ratios $\epsilon_{1,2,3,4}$ for various top-quark and Higgs-boson decay modes.
**Signal Strength**

TABLE IV. The cross-section ratios $R(t\bar{t}h)$ and $R(thX)$ with $X = j, jb, W$ defined in Eq. (9). We are taking $\sqrt{s} = 8$ TeV (LHC-8) and $C^S_t = \pm 1, \pm 1.5$.

<table>
<thead>
<tr>
<th>LHC-8</th>
<th>$C^S_t = 1$</th>
<th>$C^S_t = -1$</th>
<th>$C^S_t = 1.5$</th>
<th>$C^S_t = -1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section of $t\bar{t}h$(pb)</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(t\bar{t}h)$</td>
<td>1</td>
<td>1</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>$R(thj)$</td>
<td>0.16</td>
<td>1.86</td>
<td>0.30</td>
<td>2.82</td>
</tr>
<tr>
<td>$R(thjb)$</td>
<td>4.77e-2</td>
<td>0.59</td>
<td>9.39e-2</td>
<td>0.93</td>
</tr>
<tr>
<td>$R(thW)$</td>
<td>3.21e-2</td>
<td>0.19</td>
<td>7.05e-2</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Categories

In the $\gamma\gamma$ category for $h \to \gamma\gamma$, both CMS [7] and ATLAS [14] included all the decay modes of a top-quark pair: semileptonic ($t\bar{t} \to l\nu jjbb$), leptonic ($t\bar{t} \to l\nu\nu bb$), and hadronic ($t\bar{t} \to jjjjbb$) modes. On the other hand, in the $b\bar{b}$ category for $h \to b\bar{b}$, both CMS [7] and ATLAS [15] considered only the semileptonic and leptonic decay modes of the top-quark pair. Finally, in the categories of $ss2\ell$ and $3\ell$ for $h \to$ multileptons, both CMS [7] and ATLAS [10] included only the semileptonic decay mode of the top-quark pair.
Category Lepton for $h \rightarrow \text{multileptons}$
Category Lepton for $h \rightarrow \text{multileptons}$
Category Lepton for $h \rightarrow \text{multileptons}$
Category Lepton for $h \rightarrow \text{multileptons}$
Category diphoton for $h \rightarrow$ diphoton
Category diphoton for $h \rightarrow$ diphoton

LHC-8, CMS, $\gamma\gamma$ channel

- $C_1^S = 1$
- $C_1^S = -1$
- $C_1^S = 1.5$
- $C_1^S = -1.5$
Category bb for $h \rightarrow bb$

LHC-8, ATLAS, bb channel
Category bb for $h \rightarrow bb$
Disentangling thX from tth

\[ C^S_t = 1 \quad C^S_t = -1 \quad C^S_t = 1.5 \quad C^S_t = -1.5 \]

**FIG. 8.** The \( P_T \gamma \) distributions for the \( t\bar{t}h \) and \( thX \) processes in the \( h \rightarrow \gamma \gamma \) channel at LHC-13 taking \( C^S_t = +1, -1, +1.5, -1.5 \) from left to right. We use the Delphes ATLAS template for detector simulations.

We can separate \( thW \) from \( tth \)

the \( thW \) process has a harder \( p_T \) photon
Disentangling thX from tth

\[ C^S_t = 1 \quad C^S_t = -1 \quad C^S_t = 1.5 \quad C^S_t = -1.5 \]

We can separate thj, thjb from tth

The dominant thX processes are thj and thjb, both of which contain a very forward energetic jet.
Conclusions

• In this work, we have demonstrated explicitly that the $t\bar{t}X$ processes can significantly increase the experimentally measured signal strength $\mu(t\bar{t}h)$ when the relative sign of the top-Yukawa coupling to the gauge-Higgs coupling is reversed.

• The signal strengths can be as large as $2-4$ in the category Leptons for $h \rightarrow$ multileptons, $7-13$ in the category diphoton for $h \rightarrow$ diphoton, and $2-4$ in the category $bb$ for $h \rightarrow bb$.

• When more data are collected at 13 TeV, we can choose more specific cuts to single out the $t\bar{t}X$ processes, which can effectively determine the size and the sign of the top-Yukawa coupling.
CMS search for the Associated Higgs production with a Single Top Quark

Figure 1: Dominant Feynman diagrams for the production of $t\bar{H}q$ events: the Higgs boson is typically radiated from the heavier particles of the diagram, i.e. the $W$ boson (left) or the top quark (right).
CMS search for the Associated Higgs production with a Single Top Quark
It is time to pin down both the Sign and Size of the Top-Yukawa Coupling at the LHC NOW!!
Thank You For Your Attention!!