Extra Yukawas: Searching for New Scalars via Triple-Top Signature

Tanmoy Modak
National Taiwan University
With: M. Kohda & W.-S. Hou
Current data: 125 GeV scalar is SM-Higgs like. Indication of Alignment (approximate).

Second doublet could be rather heavy. Alignment from Decoupling.

Alignment without Decoupling: if happens, sub-TeV second doublet.
(Carena et al. JHEP '14, PRD '15; Bechtle et al. EPJC '17; See also Gunion et al. PRD '03.)

Approximate Alignment without Decoupling: Can be realized in 2HDM.
(see e.g. Hou & Kikuchi 1706.07694v3)

2HDM without $Z_2$: Extra Yukawas: $\rho_{tc}$, $\rho_{tt}$.

Sub-TeV Second Doublet + Extra Yukawas:

Novel Signatures at LHC: $cg \rightarrow tA^0/tH^0 \rightarrow ttt\bar{t}$.
Precursor: $cg \rightarrow tA^0/tH^0 \rightarrow tt\bar{c}$.

Bonus: Discovery may shed light on Baryon Asymmetry of the Universe.
(Fuyuto, Hou, Senaha PLB '18)
The Yukawa Sector

- E.g. in 2HDM-II: up- and down-type quarks get masses from different doublets.
  - Mass and Yukawa matrices are diagonalized simultaneously.
  - Realized by invoking $Z_2$ symmetry. NFC. *(Glashow, Weinberg PRD ’77)*

- 2HDM without $Z_2$: Both doublets couple with up- and down-type fermions.
  - After diagonalization of fermion mass matrices: Two different Yukawas.
    - $\kappa_f$ and $\rho_f$ with $\kappa_f = \frac{\sqrt{2}m_f}{v}$.
  - $\kappa_f$ diagonal and real; $\rho_f$ non-diagonal and in general complex.

In particular for up-type quark:

$$-rac{1}{\sqrt{2}} \bar{u}(\kappa_u c_{\beta-\alpha} - \rho_u s_{\beta-\alpha}) P_R u H^0 + \frac{i}{\sqrt{2}} \bar{u} \rho_u P_R u A^0 + h.c.$$ 

$$\begin{bmatrix} H^0 \\ h^0 \end{bmatrix} = \begin{bmatrix} c_{\beta-\alpha} & s_{\beta-\alpha} \\ -s_{\beta-\alpha} & c_{\beta-\alpha} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}$$
In alignment limit: \( c_{\beta-\alpha} = 0 \) : for simplicity

\[
\frac{\rho_{ij}}{\sqrt{2}} \bar{u}_i L (H^0 + i A^0) u_j R + \text{h.c.}
\]

- \( \rho_{ij} \): could share same flavor organization features as SM

**Trickling down off-diagonal elements**

- \( \rho_{bb} \sim \kappa_b, \rho_{\tau\tau} \sim \kappa_\tau \) and \( \rho_{tt}, \rho_{tc} \sim \kappa_t \approx 1 \).

- Complex \( \rho_{tt} \) of \( O(1) \) strength can drive EWBG. For small \( |\rho_{tt}| \), \( O(1) \rho_{tc} \) with maximal phase. (Fuyuto, Hou, Senaha PLB '18)

- B physics constraint: \( \rho_{ct} \approx 0 \). (Chen et al. PLB '13, Altunkaynak et al. PLB '15)
Signatures at LHC

- \( gg \to A^0/H^0 \to t\bar{t} \): interference with \( gg \to t\bar{t} \). (ATLAS PRL '18)

  Recent ATALS study: could be sensitive. (CMS-PAS-B2G-16-025)

  \( \rightarrow \) study above \( t\bar{t} \) threshold

- Other search modes:

  \( gg \to t\bar{t}A^0/H^0 \to t\bar{t}t\bar{t}, tt\bar{t}\bar{c} \)

  (Craig, et al., JHEP '15, '17; Kanemura et al. NPB '15; Gori et al. PRD '16)

- \( gg \to A^0/H^0 \to t\bar{c} \): Could be discovered. (Altunkaynak et al. PLB '15)

  suffers from \( t + j \) mass resolution.

  (CMS-PAS-B2G-16-025)
**Triple-top:**

\[ cg \rightarrow tS^0 \rightarrow tt\bar{t} \]

where, \( S^0 \equiv A^0 \) or \( H^0 \)

1. SM 3\( t \) at fb level.

2. Clean 3\( b \)-jets, 3-lepton final state

(See also Hou et al. PLB '97)

**Same-sign top:**

\[ cg \rightarrow tS^0 \rightarrow tt\bar{c} \]

May emerge earlier than triple-top

(See also Hou et al. PLB '97)

**Assumed nearly degenerate heavy scalars to forbid:**

\[ H^0 \rightarrow A^0 Z, H^\pm W^\mp \text{ or reverse.} \]
Parton level cross sections

Parton level cross sections at LO:

\[
\begin{align*}
\sigma(pp \to tS^0) & \quad \sqrt{s} = 14 \text{ TeV} \\
\sigma(pp \to t\bar{t}A^0) & \quad \text{fixed } \rho_{tt} = 1 \\
\sigma(pp \to t\bar{t}H^0) & \quad \text{PDF set: NN23LO1} \\
\end{align*}
\]

MadGraph5_aMC@NLO

For \( \Gamma_{H^0} = \Gamma_{A^0} \) and \( m_{A^0} = m_{H^0} \),

\[ pp \to tA^0 \to t\bar{t}\bar{c} \] and \[ pp \to tH^0 \to t\bar{t}\bar{c} \]

cancels each other exactly.
Same-sign top

Process:

\[ pp \rightarrow tS^0 + X \rightarrow tt\bar{c} + X \]

Event selection:

2 same-sign leptons \((e, \mu)\) 
+ \(\geq 3\) jets with 2\(b\)-tagged

denoted as \((SS-2\ell)\)

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ttZ)</td>
<td>0.04</td>
</tr>
<tr>
<td>(ttW)</td>
<td>0.72</td>
</tr>
<tr>
<td>(tZ) + jets</td>
<td>0.001</td>
</tr>
<tr>
<td>(3t + j)</td>
<td>0.0002</td>
</tr>
<tr>
<td>(3t + W)</td>
<td>0.0004</td>
</tr>
<tr>
<td>(tt\bar{t})</td>
<td>0.024</td>
</tr>
<tr>
<td>(4t)</td>
<td>0.04</td>
</tr>
<tr>
<td>(Q)-flip</td>
<td>0.04</td>
</tr>
</tbody>
</table>

+Non-prompt \(\sim 1.5 \times ttW\) \hspace{1cm} (CMS EPJC ’17)

Signal at LO. Backgrounds with QCD corrections included.
Discovery potential:

- $H^0$ or $A^0$ alone: $5\sigma$ for $\rho_{tc} = 1$ and $m_{S^0} \lesssim 550$ GeV.
- Discovery: easier for small $H^0 - A^0$ mass splitting case.
- Discovery could indicate $\rho_{tc}$ driven BAU.
Triple-top

Process:

\[ pp \rightarrow tS^0 + X \rightarrow tt\bar{t} + X \]

Event selection:

at least 3 leptons, \( E_T^{\text{miss}} \geq 3 \text{jets with} \geq 3b \text{ tagged} \)

denoted as \((3b3\ell)\)

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>Cross section (fb)</th>
<th>parenthesis:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ttZ + \text{jets} )</td>
<td>0.0205 (0.0026)</td>
<td>impact of Z-pole veto</td>
</tr>
<tr>
<td>( ttWb )</td>
<td>0.0017 (0.0015)</td>
<td>Z-pole veto</td>
</tr>
<tr>
<td>( tZjb )</td>
<td>0.0002 (—)</td>
<td></td>
</tr>
<tr>
<td>( 3t + j )</td>
<td>0.0001 (0.0001)</td>
<td></td>
</tr>
<tr>
<td>( 3t + W )</td>
<td>0.0004 (0.0003)</td>
<td></td>
</tr>
<tr>
<td>( tt\bar{t} )</td>
<td>0.0015 (0.0013)</td>
<td></td>
</tr>
<tr>
<td>( 4t )</td>
<td>0.0232 (0.0209)</td>
<td></td>
</tr>
<tr>
<td>( tt + \text{jets (fake)} )</td>
<td>0.0026 (0.0025)</td>
<td></td>
</tr>
</tbody>
</table>

Signal at LO. Backgrounds with QCD corrections included.
5σ for H⁰ or A⁰ only case: e.g. if $\rho_{tc} = 1$, $\rho_{tt} = 1$ and $m_{S^0} \lesssim 650$ GeV.

For $H^0$ and $A^0$ degenerate case: significances are boosted by the addition of $H^0$ and $A^0$ contributions.

\[
\mathcal{Z} = \sqrt{2[(S + B) \ln(1 + S/B) - S]}
\]
Summary

- 2HDM without $Z_2$: Extra Yukawa $\rho_{tt}$ and FCNH: $\rho_{tc}$.

- **Extra Yukawas**: leading to novel signatures at LHC.

- **Triple-top** may require HL-LHC, however **Same-sign top** may emerge with 300 fb$^{-1}$ data.

- Discovery may help understand the **Matter-Antimatter asymmetry** of the Universe.
Thank You
Backups:

CP conserving 2HDM without $Z_2$:

$$V(\Phi, \Phi') = \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 |\Phi'|^2 - (\mu_{12}^2 \Phi^\dagger \Phi' + \text{h.c.})$$

$$+ \frac{\eta_1}{2} |\Phi|^4 + \frac{\eta_2}{2} |\Phi'|^4 + \eta_3 |\Phi|^2 |\Phi'|^2 + \eta_4 |\Phi^\dagger \Phi'|^2$$

$$+ \left\{ \frac{\eta_5}{2} (\Phi^\dagger \Phi')^2 + \left[ \eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2 \right] \Phi^\dagger \Phi' + \text{h.c.} \right\}$$

Near Alignment:

$$c_\gamma \simeq \frac{-\eta_6 v^2}{m_H^2 - m_h^2} \quad \quad \cos(\beta - \alpha) \simeq \frac{-Z_6 v^2}{m_H^2 - m_h^2}$$

Exact alignment: $c_\gamma$ or $\cos(\beta - \alpha) = 0$.

Current limit: $|c_\gamma| \sim 0.3$

Alignment without decoupling:

$$|c_\gamma| \simeq 0.1 \text{ even with } |\eta_6| \text{ or } |Z_6| \sim \mathcal{O}(1)$$

and $m_H \lesssim 1 \text{ TeV}$

(Barnon et al. PRD '15,
Barnon et al. PRD '15,
Hou and Kikuchi, 1706.07694v3)

Excellent scope for LHC search

Strong 1st order EWPT

All dimensionless parameters in Higgs potential could be $\mathcal{O}(1)$
ATLAS same-sign top search (Run-1 data) (JHEP ’15). No Run-2 update.

$cc \rightarrow tt$ via $t –$ channel $A^0/H^0$


CMS search 2 SS2l, b-jets+MET (2016 data) (EPJC ’17). We utilize Exclusive SR5

CMS 4 top search (2016 data) (EPJC ’18). Could be most relevant.