Anatomy of the $tthh$ Physics at HL-LHC

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Motivation

Higgs self-coupling is the key to probe Higgs nature.

A lot of efforts have been made using $pp \rightarrow hh$ channel:

[1801.06093, 1802.04319, 1308.6302, 1301.3492, 1606.09408, 1803.04359, 1506.03302, 1205.5444, 1606.03302, 1205.5444, ......(would be a long list)]
Pessimistic Projections at HL-LHC:
[ATL-PHYS-PUB-2016-023]

| Sample                        | No cuts | Trigger | One lepton | ≥7 jets | ≥5 b-tags | η(b_i, b_j) | ≥6 b-tags |
|-------------------------------|---------|---------|------------|---------|-----------|------------|-----------|
| t\bar{t}HH(HH → b\bar{b}b\bar{b}) | 990     | 513     | 253        | 139     | 29        | 25         | 6         |
| t\bar{t}H(H → b\bar{b}) + jets | 610,000 | 500,000 | 290,000    | 69,000  | 1,580     | 1,200      | 90        |
| t\bar{t}Z(Z → b\bar{b}) + jets | 270,000 | 220,000 | 125,000    | 26,000  | 600       | 390        | 30        |
| t\bar{t}b\bar{b} + jets       | 5,900,000 | 4,800,000 | 2,800,000  | 460,000 | 9,700     | 5,500      | 400       |
| total background              | 6,800,000 | 5,500,000 | 3,200,000  | 550,000 | 11,900    | 7,100      | 520       |

Meanwhile: tthh final states also found in new resonance productions in BSM such as:

- ttH production with H → hh decay (2HDM, MSSM...)
- TT (Top Partner) with T → th (Composite Higgs Models)

0.25-0.3 σ at HL-LHC?
Cross Section Crisis

Xsec of di-Higgs production @ 14 TeV: ~35 fb
Xsec of tthh production @ 14 TeV: ~1 fb!

For SM, ~ 3000 tthh events produced @ HL-LHC

⇒ γγ final states are too scarce for HL-LHC.
(Potentially useful for future colliders...)
Different Final States

Multi-\(b+1\) lepton:

Same-sign di-lepton:

- High multiplicity
- Large combinatorial backgrounds
Multivariable Analysis
Use Boosted Decision Tree (BDT)

Correlations between different objects:

\[ \Delta R, \Delta \eta, \text{invariant mass} \ldots \]

Reconstructed Objects:

We reconstruct more object than usually needed in order to be resilient:
2 tops and 3 Higgs are reconstructed

Low level information:

\[ p_T \text{ of leptons/ } H_T/ N_{\text{jet}} \ldots \]
5 exclusive channels are analysed with BDT:

5(or more)\(b\)+1 lepton

5(or more)\(b\) + OS dilepton

SS dilepton (w/ >=4 b jets)

Multi-lepton (w/ >=4 b jets)

2\(\tau\) jets (w/ >=4b jets & 1 lepton)
The two leading channels

Multi-b + lepton: Dominant background $tt+4b$

Same-sign dilepton/ Multilepton: Dominant background $tttt$
### Multivariable Analysis (Result)

|                  | No cut | Preselection | 5b1\(\ell\)  | 5b2\(\ell\)  | SS2\(\ell\) | Multi-\(\ell\) | \(\tau\tau\) |
|------------------|--------|--------------|---------------|---------------|--------------|----------------|--------------|
| \(tthh\)        | 2.9e3  | 7.37e2       | 50.9 (97.2)   | 6.1 (12.0)    | 14.6 (15.7)  | 8.6 (9.2)     | 3.6 (3.8)    |
| \(tt4b\)        | 1.1e6  | 1.79e5       | 6.56e3 (1.31e4) | 664 (1.30e3) | 212 (223)    | 115 (121)     | 94.1 (95.1)  |
| \(tt2b2c\)      | 3.1e5  | 4.28e4       | 621 (1.73e3)  | 59.4 (163)    | 38.0 (42.4)  | 24.1 (26.8)   | 43.6 (48.6)  |
| \(ttVV\)        | 4.4e4  | 3.64e3       | 20.7 (52.7)   | 3.5 (6.4)     | 51.8 (60.9)  | 32.4 (36.5)   | 3.1 (3.9)    |
| \(4t\)          | 3.54e4 | 1.30e4       | 350 (804)     | 68.3 (152)    | 592 (635)    | 307 (324)     | 59.8 (64.2)  |
| \(ttbbV\)       | 8.29e4 | 1.54e4       | 353 (765)     | 47.8 (105)    | 114 (124)    | 203 (221)     | 22.2 (24.2)  |
| \(ttbbh\)       | 4.68e4 | 1.04e4       | 608 (1.15e3)  | 69.0 (136)    | 91.0 (98.0)  | 53.4 (56.2)   | 24.2 (25.9)  |
| \(tthV\)        | 4.65e3 | 881          | 28.1 (58.5)   | 4.1 (9.1)     | 8.8 (9.5)    | 18.5 (19.9)   | 2.3 (2.5)    |
| **Total**        | 1.6e6  | 2.65e5       | 8.53e3 (1.76e4) | 918 (1.88e3) | 1.11e3 (1.19e3) | 753 (806) | 249 (265)     |

|         | \(\sigma_{\text{cut}}\) | \(\sigma_{\text{(S/B)}_{\text{cut}}}\) | \(\sigma_{\text{BDT}}\) | \(\sigma_{\text{(S/B)}_{\text{BDT}}}\) | \(\sigma_{\text{com}}\) |
|---------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------|
|         | 0.46 (0.62)              | 0.17 (0.23)              | 0.39 (0.40)              | 0.28 (0.29)              | 0.20 (0.20)        |
| \(\sigma_{\text{BDT}}\) | 0.42 (0.40) | 0.47 (0.55) | 1.1 (1.1) | 0.9 (0.9) | 1.1 (1.1) |
| \(\sigma_{\text{(S/B)}_{\text{BDT}}}\) | 0.59 (0.79) | 0.21 (0.30) | 0.45 (0.46) | 0.33 (0.35) | 0.21 (0.21) |
| \(\sigma_{\text{com}}\) | 1.2 (1.0) | 1.3 (1.6) | 1.6 (1.6) | 1.6 (1.9) | 1.6 (1.6) |

All Channel Combined, \(~1\sigma\) @HL-LHC (Lead by multi-b + 1 lepton channel)

Comparable with other channels:
- VBF (pp → hhjj) channel: \(~0.8\sigma\) @HL-LHC
  [F. Bishara et al., 1611.03860]
- Vhh channel: <0.1\(\sigma\) @HL-LHC
  [K. Nordström and A. Papaefstathiou, 1807.01571]
A More Complete EFT Measurement

The $tthh$ contact interaction (dimension scaled by VEV) is general in Composite Higgs Models

$$\mathcal{L} \supset -y \frac{m_t}{v} tth - \kappa \frac{1}{3!} \frac{3m_h^2}{v} h^3 - c_t \frac{1}{2!} \frac{m_t}{v^2} tthh$$

Yukawa $\quad$ Trilinear $\quad$ $tthh$ contact

$$y \equiv \frac{y_{tth}}{y_{tth}^{SM}} = 1, \quad \kappa \equiv \frac{\lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}} = 1, \quad c_t = 0$$

$$\sigma(tthh)_{14} = 0.81 + 0.14\kappa + 0.04\kappa^2 + 0.28c_t + 0.21\kappa c_t + 0.44c_t^2 \text{ (fb)}$$

See also [R. Contino et al., 1205.5444]
Including Kinematic Effects

The dependence on $c_t$ is significant
Results Including Kinematic Effects

2 similar but different BDT's sensitive to $c_t / \kappa$ are trained.

Improved sensitivity in $c_t$ direction.

The result from tthh channel may help eliminating the Xsec degeneracy of gluon fusion channels at large $\kappa$. 
Future Projections (27/100 TeV)

Larger $c_t$ and $\kappa$ sensitivity

$\sigma(tthh)_{27} = 3.81 + 0.53\kappa + 0.24\kappa^2 + 0.99c_t + 1.25\kappa c_t + 3.59c_t^2$ (fb)

$\sigma(tthh)_{100} = 56.5 + 4.61\kappa + 6.30\kappa^2 + 10.3c_t + 27.4\kappa c_t + 116.9c_t^2$ (fb)
The sensitivity to both of the total Xsec change and $c_t$ induced kinematics further constrains the shape.

Including Higgs to diphoton final states will further improve the performance: Topic for future studies!

The major SM backgrounds increase by a factor $\sim 5.7$ @27 TeV

$\sim 105$ times larger background Xsec @100 TeV
In type II 2HDM (and hence SUSY models!), \( H \rightarrow hh \) decay is important when \( m_H < 350 \text{ GeV} \) and still survives until ~500 GeV.

Top partners have typical BR(T→th) ~ 25% - 50%

QCD Pair production: \( \sigma(TT^c) \sim 1 \text{ fb} \) when \( m_T \sim 1.6 \text{ TeV} \)
Resonance $tt+H$ production

The resonance searches are still lead by multiple $b$ channels

Up to $\sim 450$ GeV when $\tan \beta = 1$

Low $\tan \beta$: larger $ttH$ production

comparable with other channels rely on $pp \rightarrow H$, such as $H \rightarrow \tau \tau$
tthh final state can solely constraint BR(T → th)~50% case up to ~1.7 TeV, and BR(T → th)~50% case up to ~1.5 TeV.

When BR(T → th) becomes small, shall combine with other channels.
Gordon Research Seminar (Jun. 29-30)
Gordon Research Conference (Jun. 30 – Jul. 5)

Application Still Opens Until June 1!
Thank you!
Let's take a break.
Backup Slides
Triggers Considered (Following ATLAS)

1. Single lepton trigger: one isolated lepton with $p_T > 25$ GeV.

2. Two lepton trigger: two isolated leptons. Electrons need to have $p_T > 17$ GeV and muons $p_T > 14$ GeV.

3. Three muon trigger: at least three isolated muons.

4. Four $b$-jet trigger: at least four $b$ jets (77% tagging efficiency), or two $b$-jets (85%) + two $b$-jets (70%), with each of them having $p_T > 35$ GeV.

5. $3b + j$ trigger: at least three $b$-jets (70%) and one extra jet, with both having $p_T > 35$ GeV.

6. Di-$\tau$ trigger: two $\tau$-jets with the leading(sub) one's having $p_T > 35(25)$ GeV.

7. $\tau + \ell$ trigger: one $\tau$ jet with $p_T > 25$ GeV and one $e(\mu)$ with $p_T > 17(14)$ GeV.
## Resonance: Numerical Results

| | 5b1\ell\ (fb) | 5b2\ell\ (fb) | SS2\ell\ (fb) | Multi-\ell\ (fb) | \(\tau\tau\) (fb) | Combined (fb) |
|---|---|---|---|---|---|---|
| \(ttH,\ m_H = 300\ \text{GeV}\) | 3.6 (2.4) | 10 (7.4) | 6.8 (6.5) | 9.2 (8.9) | 12 (11) | 2.5 (2.2) |
| \(ttH,\ m_H = 500\ \text{GeV}\) | 2.6 (2.0) | 7.6 (5.7) | 5.3 (5.1) | 7.4 (7.2) | 8.0 (7.7) | 2.0 (1.6) |
| \(TT,\ m_T = 1500\ \text{GeV}\) | 0.33 (0.27) | 1.4 (1.2) | 0.87 (0.81) | 1.1 (1.0) | 1.5 (1.5) | 0.24 (0.21) |
| \(TT,\ m_T = 1750\ \text{GeV}\) | 0.31 (0.25) | 2.4 (1.5) | 0.64 (0.62) | 0.87 (0.83) | 1.4 (1.4) | 0.20 (0.17) |
| \(TT,\ m_T = 2000\ \text{GeV}\) | 0.35 (0.28) | 3.0 (2.0) | 0.63 (0.59) | 1.0 (0.94) | 2.0(1.8) | 0.22 (0.19) |
| BDT variables          | 5b1$\ell$ | 5b2$\ell$ | SS2$\ell$ | Multi-$\ell$ | $\tau\tau$ |
|------------------------|-----------|-----------|-----------|--------------|-------------|
| $N_j$                  | ✓         | ✓         | ✓         | ✓            | ✓           |
| $H_T$                  | ✓         | ✓         | ✓         | ✓            | ✓           |
| MET                    | ✓         | ✓         | ✓         | ✓            | ✓           |
| $M_T$                  | ✓         | /         | /         | /            | /           |
| Leverage [43]          | /         | ✓         | ✓         | ✓            | /           |
| Max/Avg($\Delta\eta_{bb}$) | ✓       | ✓         | ✓         | ✓            | ✓           |
| Min/Max/Avg($m_{b\bar{b}}$) | ✓     | ✓         | ✓         | ✓            | ✓           |
| Min/Avg($R_{b\ell}$)  | ✓         | ✓         | ✓         | ✓            | ✓           |
| Centrality($b/j$)     | ✓         | ✓         | ✓         | ✓            | ✓           |
| $p_T(b_i)$             | 5, 6      | 3-6       | 1-4       | 2-4          | 2-4         |
| $p_T(j_i)$             | 4         | /         | 1-3       | 2            | 2-3         |
| $p_T(\ell_i)$         | 1         | 1, 2      | 1, 2      | 1-3          | 1           |
| $\eta(\ell_i)$        | 1         | 1, 2      | 1, 2      | 1-3          | 1           |
| $p_T$(fat $j_i$)       | 1         | 1         | 1         | 1            | /           |
| $m$(fat $j_i$)         | 1         | 1         | 1         | 1, 2         | /           |
| $O(t_i)$               | 1, 2      | 1, 2      | 1, 2      | 1, 2         | 1, 2        |
| $O(h_i)$               | 1-3       | 1-3       | 1-3       | 1-3          | 1-3         |
| $R_{b_i,t_j}$          | /         | /         | 1, 2      | /            | /           |
| $R_{\ell_i,h_j}$      | i=1, j=1, 2 | /         | i=1, 2, j=1, 2 | i=1, j=1, 2 | /          |
| $R_{b_i,h_j}$          | 1-3       | 1-3       | 1-3       | 1-3          | 1-3         |
| $R_{b_i,\ell_j}$      | i=1, j=1  | i=1, j=1, 2 | /         | /            | /           |
| $R_{\ell_i,t_j}$      | i=1-3, j=1 | i=1, 2, j=1, 2 | i=1, 2, j=2 | i=1, j=1-3  | i=1, 2, j=1 |
| $m_{\ell_i,\ell_j}$   | /         | 1, 2      | 1, 2      | 1-3          | /           |
| $p_T(\tau\tau/\ell\ell)$ | /      | ✓         | /         | /            | /           |
| $\eta(\tau\tau/\ell\ell)$ | /      | ✓         | /         | /            | /           |
| $R_{\ell_i,\tau\tau/\ell\ell}$ | /    | 1, 2      | /         | /            | 1           |
| $R_{h_i,\tau\tau/\ell\ell}$ | /    | 1, 2      | /         | /            | 1, 2        |
| $M_{\ell_i,\tau\tau}$ | /         | /         | /         | /            | 1           |
Di-Higgs EFT Pheno
Reprojected from: [R. Contino et al., 1205.5444] & [C. Chen and I. Low, 1405.7040]