Search for the Higgs boson in the $t\bar{t}H$ production mode using the ATLAS detector

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on behalf of the ATLAS collaboration

Large Hadron Collider Physics Conference, June 2nd, 2014
Introduction

- Higgs boson with $m \approx 125$ GeV discovered via $\gamma\gamma$, $ZZ$, $WW$ decays
- Higgs boson Yukawa couplings probe flavor structure of the SM
- Higgs Yukawa couplings accessible at LHC: $\tau$, $\mu$, $b$ and top quark
- Strong evidence for $H \rightarrow \tau\tau$: $4.1\sigma$ for ATLAS and $3.2\sigma$ for CMS

Evidently the Higgs system knows something that we do not know: the difference between the generations - Martinus Veltman.
Higgs-top quark coupling

$\bar{t}tH$ coupling
- Drives SM properties at high energy scale
- Indirect measurement via gluon fusion production
- Direct measurement via $\bar{t}tH$ production

$\bar{t}tH$ production:
- $\sigma(\bar{t}tH) \approx 130$ fb for $m_H = 125$ GeV at $\sqrt{s} = 8$ TeV
- $\approx 2600$ events with $20.3$ fb$^{-1}$
- Main background is $\bar{t}t +$ jets with $\sigma \approx 250$ pb

Decay modes:
- $B(H \rightarrow b\bar{b}) = 0.58$ - dominant mode
- $B(H \rightarrow \gamma\gamma) = 2.3 \times 10^{-3}$ - clean resonance signature
- $B(H \rightarrow WW, ZZ, \tau\tau) \approx 0.3$ - multi-lepton final states
$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

- Tag $t\bar{t}$ decay by 1-lepton and 2-lepton
- Categorize by number jets and b-jets
- Increase sensitivity with different S/B
- Constrain systematic uncertainty by fitting regions with low S/B

1-lepton:
- $t\bar{t}H \rightarrow$ 6 jets 4 b-jets
- 1 electron or muon
- $\geq$ 4 jets
- $\geq$ 2 b-jets

2-lepton:
- $t\bar{t}H \rightarrow$ 4 jets 4 b-jets
- 2 electron or muon
- $\geq$ 2 jets
- $\geq$ 2 b-jets

$\Rightarrow$ $t\bar{t}H$ signal $> 90\%$
$t\bar{t}H \to t\bar{t} + b\bar{b}$ analysis strategy

- Tag $t\bar{t}$ decay by 1-lepton and 2-lepton
- Categorize by number jets and b-jets
- Increase sensitivity with different S/B
- Constrain systematic uncertainty by fitting regions with low S/B

1-lepton:
- $t\bar{t}H \to 6$ jets 4 b-jets
- 1 electron or muon
- $\geq 4$ jets
- $\geq 2$ b-jets

2-lepton:
- $t\bar{t}H \to 4$ jets 4 b-jets
- 2 electron or muon
- $\geq 2$ jets
- $\geq 2$ b-jets

$S/\sqrt{B}$ for control regions
$S/\sqrt{B}$ for signal regions
\[ t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \text{ analysis strategy} \]

- Tag \( t\bar{t} \) decay by 1-lepton and 2-lepton
- Categorize by number jets and b-jets
- Increase sensitivity with different S/B
- Constrain systematic uncertainty by fitting regions with low S/B

**1-lepton:**
- \( t\bar{t}H \rightarrow 6 \text{ jets } 4 \text{ b-jets} \)
- 1 electron or muon
- \( \geq 4 \) jets
- \( \geq 2 \) b-jets

**2-lepton:**
- \( t\bar{t}H \rightarrow 4 \text{ jets } 4 \text{ b-jets} \)
- 2 electron or muon
- \( \geq 2 \) jets
- \( \geq 2 \) b-jets

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**ATLAS** Preliminary Simulation
\( \sqrt{s} = 8 \text{ TeV}, \int L \, dt = 20.3 \text{ fb}^{-1} \)

**Dilepton**
\( m_h = 125 \text{ GeV} \)

\[
\begin{array}{c|c|c}
\text{S/B} & \text{Region} & \text{Value} \\
\hline
< 0.1\% & 2 \text{ jets } 2 \text{ b-jets} & \\
0.1\% & 3 \text{ jets } 2 \text{ b-jets} & 0.7\% \\
0.3\% & 4 \text{ jets } 2 \text{ b-jets} & 1.8\% \\
0.6\% & 4 \text{ jets } 3 \text{ b-jets} & 6.8\% \\
\end{array}
\]

\[ S/\sqrt{B} \text{ for control regions} \]
\[ S/\sqrt{B} \text{ for signal regions} \]
$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$: backgrounds

$t\bar{t} + \text{jets}$

- Dominant background
- $+5\%$ $-6\%$ uncertainty
- Modeled with Powheg+Pythia
- Difference between Powheg and Madgraph is taken as uncertainty
- $p_T^{t\bar{t}}$ and $p_T^t$ are re-weighted to unfolded 7 TeV data
- $t\bar{t} + b\bar{b}$ same final state as signal

Other backgrounds:

- $t\bar{t}W/Z$ - Madgraph+Pythia
- $W/Z+\text{jets}$ - Alpgen+Pythia
- Diboson - Alpgen+Herwig
- QCD multi-jet - data-driven

1-lepton background composition

ATLAS
Preliminary Simulation
$m_H = 125$ GeV
$\sqrt{s} = 8$ TeV

Single lepton
$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$: backgrounds

$t\bar{t} + \text{jets}$

- Dominant background
- +5% −6% uncertainty
- Modeled with Powheg+Pythia
- Difference between Powheg and Madgraph is taken as uncertainty
- $p_T^{t\bar{t}}$ and $p_T^t$ are re-weighted to unfolded 7 TeV data
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Other backgrounds:

- $t\bar{t}W/Z$ - Madgraph+Pythia
- $W/Z+\text{jets}$ - Alpgen+Pythia
- Diboson - Alpgen+Herwig
- QCD multi-jet - data-driven

### 1-lepton yields - post-fit

<table>
<thead>
<tr>
<th></th>
<th>5 jets, $\geq 4$ $b$-tags</th>
<th>6 jets, $\geq 3$ $b$-tags</th>
<th>6 jets, $\geq 4$ $b$-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H (125)$</td>
<td>$11 \pm 1 \pm 9$</td>
<td>$69 \pm 3 \pm 57$</td>
<td>$28 \pm 2 \pm 23$</td>
</tr>
<tr>
<td>$t\bar{t} + \text{light}$</td>
<td>$78 \pm 9$</td>
<td>$2380 \pm 130$</td>
<td>$78 \pm 11$</td>
</tr>
<tr>
<td>$t\bar{t} + c\bar{c}$</td>
<td>$45 \pm 12$</td>
<td>$750 \pm 190$</td>
<td>$75 \pm 19$</td>
</tr>
<tr>
<td>$t\bar{t} + b\bar{b}$</td>
<td>$149 \pm 20$</td>
<td>$1160 \pm 170$</td>
<td>$300 \pm 40$</td>
</tr>
<tr>
<td>$t\bar{t} + V$</td>
<td>$3.3 \pm 1.0$</td>
<td>$44 \pm 13$</td>
<td>$8.9 \pm 2.7$</td>
</tr>
<tr>
<td>non-$t\bar{t}$</td>
<td>$23.2 \pm 2.5$</td>
<td>$218 \pm 23$</td>
<td>$18.8 \pm 2.2$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$309 \pm 11$</td>
<td>$4620 \pm 80$</td>
<td>$507 \pm 27$</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>283</td>
<td>4671</td>
<td>516</td>
</tr>
</tbody>
</table>
\( t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \): multi-variate discriminant inputs

- Event shape variables: event centrality, ...
- Object pair properties: \( m_{bb}^{\text{min}\Delta R} \), ...
- Object kinematics: \( p_T^{\text{jet}} \), ...
- Event kinematics: \( H_T^{\text{had}}, N_{p_T > 40 \text{ GeV}}, \) ...
- Modeling of variables and correlations checked in signal depleted regions

1-lepton centrality = \( \sum p_T / \sum E \)

2-lepton \( m_{bb}^{\text{min}\Delta R} \)
$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$: multi-variate discriminant output

- Neural Network trained in each signal region
- Select 10 highest rank variables with NeuroBayes
- Use all MC events - weight light jets with b-jet mistag rate maps

### 1-lepton
$\quad t\bar{t}H \rightarrow 6$ jets $4$ b-jets

### 2-lepton
$\quad t\bar{t}H \rightarrow 4$ jets $4$ b-jets
$t\bar{t}$ + jets control regions

1-lepton 4 jet $\geq 4$ b

$H_T^{\text{had}} = \sum p_T^{\text{jet}}$

$H_T = \sum p_T^{\text{jet}} + \sum p_T^{\text{lepton}}$

- $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$ are constrained from fits to signal depleted regions
Signal and control region yields

1-lepton yields post-fit

2-lepton yields post-fit

- Simultaneous binned likelihood fit to 6 signal and 9 control regions
- Measure $t\bar{t}H$ signal strength $\mu$ and background normalization
- $\mu = 1$ corresponds to SM $t\bar{t}H$ prediction
\( t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \): systematic uncertainties

Main systematic uncertainties

- \( t\bar{t} + \) heavy flavor normalization
- Jet flavor tagging
- \( t\bar{t} \) re-weighting to data and Madgraph
- \( t\bar{t} \) theoretical uncertainties
- Reduced by fitting data

<table>
<thead>
<tr>
<th></th>
<th>( t\bar{t} ) + light</th>
<th>( t\bar{t} + c\bar{c} )</th>
<th>( t\bar{t} + b\bar{b} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pre-fit</td>
<td>±30</td>
<td>±57</td>
<td>±56</td>
</tr>
<tr>
<td>Total post-fit</td>
<td>±14</td>
<td>±25</td>
<td>±14</td>
</tr>
</tbody>
</table>

\[ \mu \Delta \theta = (\theta - \theta_o) / \Delta \theta \]

\[ m_t = 125 \text{ GeV} \]

ATLAS Preliminary
$t\bar{t}H \to t\bar{t} + b\bar{b}$: results

- **Observed (expected) 95% CL limit $4.1 \times \text{SM} (2.6 \times \text{SM})$ for $m_H = 125$ GeV**
- **Best fit $\mu = 1.7 \pm 1.4$**
- **ATLAS-CONF-2014-011**
$t\bar{t}H \to t\bar{t} + \gamma\gamma$ candidate event
$t\bar{t}H \rightarrow t\bar{t} + \gamma\gamma$: signal regions

- Hadronic $t\bar{t}$ channel: $\geq 6$ jet $\geq 2$ b - $N_{\text{signal}} = 0.36$
- Leptonic $t\bar{t}$ channel: $\geq 1$-lepton, $\geq 1$ b - $N_{\text{signal}} = 0.55$
- 2 isolated high $p_T$ photons - search for $m_{\gamma\gamma}$ resonance
- Model $m_{\gamma\gamma}$ for background with exponential function
- Simultaneous fit to signal and control regions with relaxed kinematic cuts
$t\bar{t}H \rightarrow t\bar{t} + \gamma\gamma$: results

- Observed 95% CL limit: $5.3 \times \text{SM} \ (6.4 \times \text{SM})$ for $m_H = 126.8$ GeV
- 9-12% uncertainty on $\sigma(t\bar{t}H)$ and 5% uncertainty on $BR(H \rightarrow \gamma\gamma)$
- 4-6% uncertainty on photon id and isolation in multi-jet environment
- 5-10% uncertainty on jet energy scale and b-tagging in hadronic channel
- ATLAS-CONF-2013-080
Summary and outlook

\[ t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \]
- Observed (expected) 95% CL limit: $4.1 \times \text{SM} \ (2.6 \times \text{SM})$

\[ t\bar{t}H \rightarrow t\bar{t} + \gamma\gamma \]
- Observed (expected) 95% CL limit: $5.3 \times \text{SM} \ (6.4 \times \text{SM})$

Outlook
- Publications of improved analyses of these final states are forthcoming
- Results of multi-lepton analyses will be also published
- $t\bar{t}H$ cross-section increases by 3.9 at $\sqrt{s} = 13$ TeV compared to 8 TeV
- ATLAS pixel detector upgrade: added Insertable B-Layer
- Expect to reach SM sensitivity in Run 2
BACKUP
$t\bar{t}H \rightarrow t\bar{t} + b\bar{b}$ analysis strategy

1-lepton:
- $t\bar{t}H \rightarrow 6$ jets 4 b-jets
- 1 electron or muon with $p_T > 25$ GeV
- $\geq 4$ jets
- $\geq 2$ b-jets

2-lepton:
- $t\bar{t}H \rightarrow 4$ jets 4 b-jets
- 2 electron or muon with $p_T > 25(15)$ GeV
- $\geq 2$ jets
- $\geq 2$ b-jets
- $e\mu$: $H_T > 130$ GeV
- $ll$: $m_{ll} > 15$ GeV and Z veto
- Exactly 2 b ll: $m_{ll} > 60$ GeV

- Jets with $p_T > 25$ GeV in $|\eta| < 2.5$
- 70% b-tagging working point with 1% mis-tag
\( t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \): multi-variate discriminant output

- Neural Network trained in each signal region
- Select 10 highest rank variables with NeuroBayes
- Use all MC events - weight light jets with b-jet mistag rate maps

1-lepton 5 jet \( \geq 4 \) b

1-lepton 6 jet 3 b

1-lepton 6 jet \( \geq 4 \) b
\( t\bar{t}H \rightarrow t\bar{t} + b\bar{b} \): multi-variate discriminant output

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1-lepton 5 jet \( \geq 4 \) b

1-lepton 6 jet 3 b

1-lepton 6 jet \( \geq 4 \) b
## 1-lepton variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrality</td>
<td>Sum of the $p_T$ divided by sum of the $E$ for all jets and the lepton</td>
</tr>
<tr>
<td>H1</td>
<td>Second Fox-Wolfram moment computed using all jets and the lepton</td>
</tr>
<tr>
<td>$m_{bb}^{min \Delta R}$</td>
<td>Mass of the combination of two $b$-tagged jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$N_{40}^{jet}$</td>
<td>Number of jets with $p_T \geq 40 GeV$</td>
</tr>
<tr>
<td>$\Delta R_{bb}^{avg}$</td>
<td>Average $\Delta R$ for all $b$-tagged jet pairs</td>
</tr>
<tr>
<td>$m_{jj}^{max p_T}$</td>
<td>Mass of the combination of any two jets with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>Aplanarity$_{b-jet}$</td>
<td>$1.5 \lambda_2$, where $\lambda_2$ is the second eigenvalue of the momentum tensor built with only $b$-tagged jets</td>
</tr>
<tr>
<td>$H_{T}^{had}$</td>
<td>Scalar sum of jet $p_T$</td>
</tr>
<tr>
<td>$m_{jj}^{min \Delta R}$</td>
<td>Mass of the combination of any two jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$\Delta R_{lep-bb}^{min \Delta R}$</td>
<td>$\Delta R$ between the lepton and the combination of two $b$-tagged jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$m_{bj}^{min \Delta R}$</td>
<td>Mass of the combination of a $b$-tagged jet and any jet with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$m_{bj}^{max p_T}$</td>
<td>Mass of the combination of a $b$-tagged jet and any jet with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>$m_{uu}^{min \Delta R}$</td>
<td>Mass of the combination of two untagged jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$p_T^{jet5}$</td>
<td>Fifth leading jet $p_T$</td>
</tr>
<tr>
<td>$\Delta R_{bb}^{max p_T}$</td>
<td>$\Delta R$ between two $b$-tagged jets with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>$m_{bb}^{max m}$</td>
<td>Mass of the combination of two $b$-tagged jets with the largest invariant mass</td>
</tr>
<tr>
<td>$p_{T,uu}^{min \Delta R}$</td>
<td>Scalar sum of the $p_T$’s of the pair of untagged jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$m_{jjjj}$</td>
<td>Mass of the jet triplet with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>$\Delta R_{uu}^{min \Delta R}$</td>
<td>Minimum $\Delta R$ between two untagged jets</td>
</tr>
<tr>
<td>$m_{bb}^{max p_T}$</td>
<td>Mass of the combination of two $b$-tagged jets with the largest vector sum $p_T$</td>
</tr>
</tbody>
</table>
### 2-lepton variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{bb}$</td>
<td>Mass of the two $b$-tagged jets from the Higgs candidate system</td>
</tr>
<tr>
<td>$H_T$</td>
<td>Scalar sum of jet $p_T$ and lepton $p_T$-s</td>
</tr>
<tr>
<td>$p_{jet3}^T$</td>
<td>Third leading jet $p_T$</td>
</tr>
<tr>
<td>$p_{jet4}^T$</td>
<td>Fourth leading jet $p_T$</td>
</tr>
<tr>
<td>Centrality</td>
<td>Sum of the $p_T$ divided by sum of the $E$ for all jets and both leptons</td>
</tr>
<tr>
<td>$A_{planarity_{jet}}$</td>
<td>1.5$\lambda_2$, where $\lambda_2$ is the second eigenvalue of the momentum tensor built with all jets</td>
</tr>
<tr>
<td>$H1$</td>
<td>Second Fox-Wolfram moment computed using all jets and both leptons</td>
</tr>
<tr>
<td>$H4$</td>
<td>Fifth Fox-Wolfram moment computed using all jets and both leptons</td>
</tr>
<tr>
<td>$\Delta R_{hl}^{min}$</td>
<td>$\Delta R$ between the Higgs candidate and the closest lepton</td>
</tr>
<tr>
<td>$\Delta R_{hl}^{max}$</td>
<td>$\Delta R$ between the Higgs candidate and the furthest lepton</td>
</tr>
<tr>
<td>$N_{Higgs}^{30}$</td>
<td>Number of Higgs candidates within 30 GeV of the defined Higgs mass</td>
</tr>
<tr>
<td>$m_{jj}^{closest}$</td>
<td>Dijet mass between any two jets closest to the defined Higgs mass</td>
</tr>
<tr>
<td>$\Delta \eta_{jj}^{max}$</td>
<td>Maximum $\Delta \eta$ between any two jets in the event</td>
</tr>
<tr>
<td>$m_{jj}^{min}$</td>
<td>Minimum dijet mass between any two jets</td>
</tr>
<tr>
<td>$m_{jj}^{max}$</td>
<td>Mass of the combination of any two jets with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>$m_{bb}^{min}$</td>
<td>Mass of the combination of two $b$-tagged jets with the smallest $\Delta R$</td>
</tr>
<tr>
<td>$\Delta R_{bj}^{min}$</td>
<td>Minimum $\Delta R$ between a $b$-tagged jet and any jet</td>
</tr>
<tr>
<td>$\Delta R_{lj}^{min}$</td>
<td>Minimum $\Delta R$ between any lepton and jet</td>
</tr>
<tr>
<td>$\Delta R_{bb}^{max}$</td>
<td>$\Delta R$ between two $b$-tagged jets with the largest vector sum $p_T$</td>
</tr>
<tr>
<td>$\Delta R_{bb}^{max}$</td>
<td>$\Delta R$ between two $b$-tagged jets with the largest invariant mass</td>
</tr>
</tbody>
</table>
Table: The lists and rankings of the variables considered in each of the regions in the single lepton channel where a NN is used.
<table>
<thead>
<tr>
<th>Variable</th>
<th>(≥ 4j, ≥ 4b)</th>
<th>(≥ 4j, 3b)</th>
<th>(3j, 3b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \eta_{jj} )</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( m_{bb} )</td>
<td>2</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>( m_{\overline{b}b} )</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta R_{hl} )</td>
<td>4</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>( N_{30}^{Higgs} )</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>( \Delta R_{bb}^{max} )</td>
<td>6</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Aplanarity_{jet}</td>
<td>7</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>( m_{jj}^{min} )</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>( \Delta R_{hl}^{max} )</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( m_{jj}^{closest} )</td>
<td>10</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>( H_T )</td>
<td>-</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>( \Delta R_{bb}^{max} )</td>
<td>-</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta R_{ij}^{min} )</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Centrality</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>( m_{jj}^{max} )</td>
<td>-</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>( H4 )</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>( p_T^{jet3} )</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table:** The lists and rankings of the variables considered in each of the regions in the dilepton channel where a NN is used.
$t\bar{t} + \text{jets}$ signal region composition regions

1-lepton

- $4\ j, 2\ b$
- $4\ j, 3\ b$
- $4\ j, \geq 4\ b$

2-lepton

- $2\ j, 2\ b$
- $3\ j, 2\ b$
- $3\ j, 3\ b$

Single lepton

$\geq 4\ j, 2\ b$

$\geq 4\ j, \geq 4\ b$

Dilepton

$\geq 4\ j, \geq 4\ b$

**ATLAS**

Preliminary Simulation

$m_t = 125\ \text{GeV}$

$\sqrt{s} = 8\ \text{TeV}$

- $tH, H\rightarrow b\bar{b}$
- $tH, H\rightarrow WW$
- $tH, H\rightarrow \tau\bar{\tau}$
- $tH, H\rightarrow gg$
- $tH, H\rightarrow c\bar{c}$
- $tH, H\rightarrow ZZ$
- $tH, H\rightarrow \text{others}$
$(\geq 6j, \geq 4b)$ systematic uncertainties

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}H$ (125)</th>
<th>$t\bar{t} + \text{light}$</th>
<th>$t\bar{t} + c\bar{c}$</th>
<th>$t\bar{t} + b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>$\pm 6.5$</td>
<td>$\pm 14$</td>
<td>$\pm 10$</td>
<td>$\pm 8.2$</td>
</tr>
<tr>
<td>Jet efficiencies</td>
<td>$\pm 1.6$</td>
<td>$\pm 5.4$</td>
<td>$\pm 2.5$</td>
<td>$\pm 2.4$</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>$\pm 0.1$</td>
<td>$\pm 8.5$</td>
<td>$\pm 4.1$</td>
<td>$\pm 4.3$</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>$\pm 9.0$</td>
<td>$\pm 5.8$</td>
<td>$\pm 5.1$</td>
<td>$\pm 9.2$</td>
</tr>
<tr>
<td>$c$-tagging efficiency</td>
<td>$\pm 1.9$</td>
<td>$\pm 7.3$</td>
<td>$\pm 14$</td>
<td>$\pm 2.8$</td>
</tr>
<tr>
<td>Light jet-tagging efficiency</td>
<td>$\pm 1.0$</td>
<td>$\pm 17$</td>
<td>$\pm 4.4$</td>
<td>$\pm 1.5$</td>
</tr>
<tr>
<td>$t\bar{t}$ modelling: reweighting</td>
<td>–</td>
<td>$\pm 11$</td>
<td>$\pm 13$</td>
<td>$\pm 13$</td>
</tr>
<tr>
<td>$t\bar{t}$ modelling: parton shower</td>
<td>–</td>
<td>$\pm 7.5$</td>
<td>$\pm 1.8$</td>
<td>$\pm 10$</td>
</tr>
<tr>
<td>$t\bar{t}$ heavy-flavour: normalisation</td>
<td>–</td>
<td>–</td>
<td>$\pm 50$</td>
<td>$\pm 50$</td>
</tr>
<tr>
<td><strong>Total pre-fit</strong></td>
<td>$\pm 12$</td>
<td>$\pm 30$</td>
<td>$\pm 57$</td>
<td>$\pm 56$</td>
</tr>
<tr>
<td><strong>Total post-fit</strong></td>
<td>$\pm 7.2$</td>
<td>$\pm 14$</td>
<td>$\pm 25$</td>
<td>$\pm 14$</td>
</tr>
</tbody>
</table>
$t\bar{t} + \text{jets signal regions}$

**ATLAS** Preliminary

$\sqrt{s}$ = 8 TeV, $\int L \, dt = 20.3$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Region</th>
<th>Expected ± 1σ</th>
<th>Expected ± 2σ</th>
<th>Observed</th>
<th>Expected ($\mu$=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lepton+jets</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Combination</td>
<td></td>
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</tr>
</tbody>
</table>

95% CL limit on $\sigma/\sigma_{SM}$ at $m_H=125$ GeV

- Lepton+jets: 1.7 ± 1.4 (0.7)
- Dilepton: 2.9 ± 2.3 (1.4)
- Combination: 1.7 ± 1.4 (0.7)

ATLAS Preliminary

$\sqrt{s}$ = 8 TeV, $\int L \, dt = 20.3$ fb$^{-1}$

Comb. Single lepton and Dilepton

<table>
<thead>
<tr>
<th>Data / Bkgd.</th>
<th>$10^{-4}$</th>
<th>$10^{-3.5}$</th>
<th>$10^{-3}$</th>
<th>$10^{-2.5}$</th>
<th>$10^{-2}$</th>
<th>$10^{-1.5}$</th>
<th>$10^{-1}$</th>
<th>$10^{-0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events / bin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- $t\bar{t}H (\mu_{LT}=1.7)$
- $t\bar{t}H (\mu_{95\% \, \text{excl}}=4.1)$
$t\bar{t}H \rightarrow t\bar{t} + \gamma\gamma$: analysis strategy

- **Hadronic $t\bar{t}$ channel:** $\geq 6$ jet $\geq 2$ b - $N_{signal} = 0.36$
- **Leptonic $t\bar{t}$ channel:** $\geq 1$-lepton, $\geq 1$ b - $N_{signal} = 0.55$
- Aim for high efficiency to maximize signal yields
- 80% b-tagging working point with $\approx 4\%$ light quark jet rejection
- 2 isolated high $p_T$ photons - 40 (30) GeV
- Jets with $p_T > 25$ GeV in $|\eta| < 2.5$