Measurement of Higgs boson production in association with top quarks with ATLAS

Rencontres du Vietnam 2018, Quy Nhon

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On behalf of the ATLAS collaboration

8th August, 2018
Introduction

Higgs Yukawa couplings

- All current measurements of the Higgs boson have been consistent with SM
- Fermions couple with the Higgs boson through *Yukawa interactions*
  - Coupling strength proportional to fermion mass
  - Largest coupling is to the top quark
  - Sensitive to the scale of new physics!
- $y_t$ mainly constrained from loop processes

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Not model independent, ignores potential BSM contributions
Introduction

$t\bar{t}H$ production

- $t\bar{t}H$: More model independent test of $y_t$
  - Fourth main Higgs production at LHC
  - Direct measurement of the coupling of Higgs to top quarks

- However, very challenging to measure
  - Small cross section, $\sim 0.5$ pb at 13 TeV
  - Complex final states
  - Large irreducible backgrounds
    - $t\bar{t} + b\bar{b}$, $\mathcal{O}(2)$ magnitudes larger
    - $t\bar{t} + V$, $\sim 1.5$ pb

- Huge efforts to observe $t\bar{t}H$ production during LHC Run 1 and 2
Wide range of analyses designed to target the various Higgs boson decays

- Additional considerations to the decay of $t\bar{t}$ pair
- Final states with many objects: jets, $b$-jets, $e$, $\mu$, hadronic $\tau$, photons
- Huge thanks to the excellent detector performance magnificent effort of ATLAS performance groups
Four analyses targeting different Higgs decay modes

- Wide range of signal purity and expected yields
- Analysed separately before entering combined analysis

**$t\bar{t}H (H \rightarrow b\bar{b})$**

- $36.1 \text{ fb}^{-1}, 13 \text{ TeV}$
- $S/B \ 1.8-5.5\%$

**$t\bar{t}H$ multilepton**

- $36.1 \text{ fb}^{-1}, 13 \text{ TeV}$
- $S/B \ 5-34\%$

**$t\bar{t}H$ enriched in $H \rightarrow \gamma\gamma/4\ell$**

- $79.8 \text{ fb}^{-1}, 13 \text{ TeV}$
- $S/B \ 5-200\% (\gamma\gamma), 50-500\% (ZZ^* \rightarrow 4\ell)$
Analysis Strategy
\( t\bar{t}H (H \rightarrow b\bar{b}) \)

- Benefit from large \( H \rightarrow b\bar{b} \) BR, selects leptonic top decays
- Large irreducible background from \( t\bar{t} + \text{jets} \), especially \( t\bar{t} + \text{Heavy Flavour} \)
- Large theory uncertainties, biggest source of systematic uncertainty
- Use of MVA techniques in signal regions to enhance signal sensitivity

Categorisation
- Use \( b \)-tagging of jets and object multiplicities
- Dedicated boosted region targets high \( p_T \) top/Higgs

Reconstruction
- Solve object combinatorics to reconstruct final state
- Reco BDT, MEM and Likelihood discriminants

Classification
- BDTs for \( t\bar{t}H \) vs \( t\bar{t} + \text{jets} \)
- Optimised in all SRs
- Reconstruction + event kinematic variables

10 CRs
9 SRs
Analysis Strategy
\( t\bar{t}H (H \rightarrow b\bar{b}) \) Results

- Binned profile likelihood over all regions
- \( t\bar{t} + \geq 1b, \ t\bar{t} + \geq 1c \) normalisation factors kept free floating
- Significance of 1.4\( \sigma \) (1.6\( \sigma \) expected)
- Systematically limited by modelling of \( t\bar{t} + \text{HF} \) background

\[
\Delta \mu = 0.46 \quad \text{and} \quad -0.46
\]

\[
\text{Background-model stat. unc.} \quad +0.29 \quad -0.31
\]

\[
b\text{-tagging efficiency and mis-tag rates} \quad +0.16 \quad -0.16
\]

\[
\text{Jet energy scale and resolution} \quad +0.14 \quad -0.14
\]

\[
\text{\( t\bar{t}H \) modelling} \quad +0.22 \quad -0.05
\]

\[
\text{\( t\bar{t} + \geq 1c \) modelling} \quad +0.09 \quad -0.11
\]

\[
\text{JVT, pileup modelling} \quad +0.03 \quad -0.05
\]

\[
\text{Other background modelling} \quad +0.08 \quad -0.08
\]

\[
\text{\( t\bar{t} + \text{light} \) modelling} \quad +0.06 \quad -0.03
\]

\[
\text{Luminosity} \quad +0.03 \quad -0.02
\]

\[
\text{Light lepton (e,\( \mu \)) id., isolation, trigger} \quad +0.03 \quad -0.04
\]

\[
\text{Total systematic uncertainty} \quad +0.57 \quad -0.54
\]

\[
\text{\( t\bar{t} + \geq 1b \) normalisation} \quad +0.09 \quad -0.10
\]

\[
\text{\( t\bar{t} + \geq 1c \) normalisation} \quad +0.02 \quad -0.03
\]

\[
\text{Intrinsic statistical uncertainty} \quad +0.21 \quad -0.20
\]

\[
\text{Total statistical uncertainty} \quad +0.29 \quad -0.29
\]

\[
\text{Total uncertainty} \quad +0.64 \quad -0.61
\]
Analysis Strategy
$t\bar{t}H$ multileptons

- Target Higgs decays with leptonic final states and leptonic $t\bar{t}$ decays
- Same sign and $>3$ lepton events reduce $t\bar{t}$ background
  - Requirements on ($b$-)jet multiplicities
  - Events categorised by number of leptons & hadronic taus
  - Wide range of yields and S/B purity
  - Seven final states in total

- Object level BDTs used to reduce non-prompt leptons and charge mis-ID
- Enhance separation from $t\bar{t}$, $t\bar{t}V$ with BDTs
  - Event count in $3\ell 1\tau_{had}$ and $4\ell$
Analysis Strategy

**t\bar{t}H multileptons Results**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>2\ell OS + 1\tau_{had}</td>
<td>0.9σ</td>
</tr>
<tr>
<td>1\ell + 2\tau_{had}</td>
<td>-</td>
</tr>
<tr>
<td>4\ell</td>
<td>-</td>
</tr>
<tr>
<td>3\ell + 1\tau_{had}</td>
<td>1.3σ</td>
</tr>
<tr>
<td>2\ell SS + 1\tau_{had}</td>
<td>3.4σ</td>
</tr>
<tr>
<td>3\ell</td>
<td>2.4σ</td>
</tr>
<tr>
<td>2\ell SS</td>
<td>2.6σ</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>4.1σ</strong></td>
</tr>
</tbody>
</table>

- Binned profile likelihood across all regions
- **Observed significance of 4.1σ** for \(t\bar{t}H\) production (2.8σ exp)
- Additional cut based cross check analysis performed
  - Consistent results with the MVA based approach
  - 15% poorer sensitivity
- Leading systematics from \(t\bar{t}H\) and \(t\bar{t}V\) modelling, non-prompt lepton estimates and jet energy scale/resolution
Analysis Strategy

$t\bar{t}H (\gamma\gamma)$

- Small rate but very signal enriched regions with a continuous background
- Reconstruct Higgs as a narrow peak, use side bands to estimate background
  - Main background from non-resonant $\gamma\gamma$ and non-$t\bar{t}H$ production

- Categorise events by leptonic ($>1\ell$) and hadronic ($0\ell$) $t\bar{t}$ decays
- Train BDTs to separate $t\bar{t}H$ from background in lep and had
  - Jet/lepton 4-vector info
  - Photon observables
  - $E_T^{miss}$ and $b$-tagging
- Cut on BDT distributions to define signal rich regions
  - Seven regions in total

50% improvement in sensitivity

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Analysis Strategy
$t\bar{t}H(H \rightarrow \gamma\gamma)$

$t\bar{t}H(\gamma\gamma)$ Results

- Unbinned maximum likelihood fit over $m_{\gamma\gamma}$ in range 105 – 160 GeV
  - Non-$t\bar{t}H$ production fixed to SM prediction
  - Function for $\gamma\gamma$ background derived in each regions
    - Leptonic regions: simulation
    - Hadronic regions: data driven from control region
- Observed significance of 4.1$\sigma$ for $t\bar{t}H$ production (3.7$\sigma$ expected)
  - Measured signal strength $\mu = 1.39^{+0.48}_{-0.42} = 1.39^{+0.42}_{-0.36}$ (stat.)$^{+0.23}_{-0.17}$ (syst.)
- Currently statistically limited ($\sim$29% stat uncertainty)
Analysis Strategy

$t\bar{t}H (H \rightarrow ZZ^* \rightarrow 4\ell)$

- **Extremely low rate but very high signal to background ratio** (up to 500%)
- Look at $4\ell$ inv-mass window 115–130 GeV
- Categorise events by $t\bar{t}$ decay: leptonic (1 additional $\ell$) and hadronic (0 additional $\ell$)
  - Further split hadronic into two bins with BDT to enhance $t\bar{t}H$ purity
- **No observed events**
  - Fewer than one expected event
- Expected significance of 1.2$\sigma$
- Very statistically limited

<table>
<thead>
<tr>
<th>Region</th>
<th>$t\bar{t}H$</th>
<th>Non-$t\bar{t}H$ Higgs</th>
<th>Other bkg</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Had 2</td>
<td>0.169(31)</td>
<td>0.021(7)</td>
<td>0.008(8)</td>
<td>0</td>
</tr>
<tr>
<td>Had 1</td>
<td>0.216(32)</td>
<td>0.20(9)</td>
<td>0.22(12)</td>
<td>0</td>
</tr>
<tr>
<td>Lep</td>
<td>0.212(31)</td>
<td>0.0256(23)</td>
<td>0.015(13)</td>
<td>0</td>
</tr>
</tbody>
</table>
Combined Result

- Combination of all four analyses performed using profile likelihood method

**Fit details**

- Negligible overlap between events in each analysis
- Non-$t\bar{t}H$ Higgs production fixed to SM prediction
- Correlation scheme studied in detail

**Observation of $t\bar{t}H$ production at 13 TeV. 5.8σ observed (4.9σ expected)**

- Measured $t\bar{t}H$ cross section at $\sqrt{s} = 13$ TeV:
  \[ \sigma_{t\bar{t}H} = 670 \pm 90^{+110}_{-100} \text{(stat)} \pm 100 \text{(syst)} \text{ fb}^{-1} \]

- Cross section $1.32 \times$ SM prediction, compatible with SM at around $1\sigma$ level
Combination Result

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \)

- Some channels still very much limited by statistics
- Modelling uncertainties dominate the systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>( \Delta \sigma_{\bar{t}tH}/\sigma_{\bar{t}tH} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory uncertainties (modelling)</td>
<td>11.9</td>
</tr>
<tr>
<td>( \bar{t}t + ) heavy flavour</td>
<td>9.9</td>
</tr>
<tr>
<td>( \bar{t}tH )</td>
<td>6.0</td>
</tr>
<tr>
<td>Non-( ttH ) Higgs boson production modes</td>
<td>1.5</td>
</tr>
<tr>
<td>Other background processes</td>
<td>2.2</td>
</tr>
<tr>
<td>Experimental uncertainties</td>
<td></td>
</tr>
<tr>
<td>Fake leptons</td>
<td>9.3</td>
</tr>
<tr>
<td>Jets, ( E_T^{\text{miss}} )</td>
<td>5.2</td>
</tr>
<tr>
<td>Electrons, photons</td>
<td>4.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2</td>
</tr>
<tr>
<td>( \tau )-lepton</td>
<td>3.0</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>2.5</td>
</tr>
<tr>
<td>MC statistical uncertainties</td>
<td>1.8</td>
</tr>
</tbody>
</table>

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Combination with Run 1

▶ Combine the 13 TeV result with the ATLAS Run 1 result ▶ EPJC 76 (2016) 6
  ▶ Additional 4.5 fb\(^{-1}\) 7 TeV and 20.3 fb\(^{-1}\) 8 TeV data
  ▶ 6.3\(\sigma\) observed significance, 5.1\(\sigma\) expected!

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated</th>
<th>(t\bar{t}H) cross</th>
<th>Obs. sign.</th>
<th>Exp. sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>luminosity [fb(^{-1})]</td>
<td>section [fb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>79.8</td>
<td>710 (+210)(^{-190}) (stat.) (+120)(^{-90}) (syst.)</td>
<td>4.1 (\sigma)</td>
<td>3.7 (\sigma)</td>
</tr>
<tr>
<td>(H \rightarrow \text{multilepton})</td>
<td>36.1</td>
<td>790 (+150)(^{-140}) (stat.) (+150)(^{-140}) (syst.)</td>
<td>4.1 (\sigma)</td>
<td>2.8 (\sigma)</td>
</tr>
<tr>
<td>(H \rightarrow b\bar{b})</td>
<td>36.1</td>
<td>400 (+150)(^{-140}) (stat.) (+150)(^{-140}) (syst.)</td>
<td>1.4 (\sigma)</td>
<td>1.6 (\sigma)</td>
</tr>
<tr>
<td>(H \rightarrow ZZ^* \rightarrow 4\ell)</td>
<td>79.8</td>
<td>&lt;900 (68% CL)</td>
<td>0 (\sigma)</td>
<td>1.2 (\sigma)</td>
</tr>
<tr>
<td>Combined (13 TeV)</td>
<td>36.1–79.8</td>
<td>670 (+90)(^{-100}) (stat.) (+110)(^{-100}) (syst.)</td>
<td>5.8 (\sigma)</td>
<td>4.9 (\sigma)</td>
</tr>
<tr>
<td>Combined (7, 8, 13 TeV)</td>
<td>4.5, 20.3, 36.1–79.8</td>
<td>–</td>
<td>6.3 (\sigma)</td>
<td>5.1 (\sigma)</td>
</tr>
</tbody>
</table>
Conclusion

- Search for $t\bar{t}H$ production performed at 13 TeV using 36.1 – 79.8 fb$^{-1}$ data
- Combination of several challenging analyses
  - Extensive use of multivariate techniques to enhance sensitivity
  - Large systematic uncertainties on modelling
  - Some channels statistically limited, will only become more sensitive!
- ATLAS observation of $t\bar{t}H$ with a significance of 6.3$\sigma$ (5.1$\sigma$ exp)
  - Direct observation of top Yukawa coupling
  - Measured $\sigma_{t\bar{t}H} = 670 \pm 90$(stat)$^{+110}_{-100}$(syst) fb$^{-1}$ at 13 TeV
  - Consistent with SM prediction $\sigma_{t\bar{t}H} = 507^{+35}_{-50}$ fb$^{-1}$
Backup
\[ \frac{\sigma_{\text{ttH}}}{\sigma_{\text{SM}}} \]

\[ \begin{align*}
\text{ttH (b\bar{b})} & : 0.79 \pm 0.61 (\pm 0.29, \pm 0.30) \\
\text{ttH (multilepton)} & : 1.56 \pm 0.42 (\pm 0.30, \pm 0.30) \\
\text{ttH (\gamma\gamma)} & : 1.39 \pm 0.48 (\pm 0.38, \pm 0.23) \\
\text{ttH (ZZ)} & : < 1.77 \text{ at 68\% CL} \\
\text{Combined} & : 1.32 \pm 0.28 (\pm 0.18, \pm 0.21) 
\end{align*} \]

\[ \begin{align*}
\text{Total} & = 13 \text{ TeV, 36.1 - 79.8 fb}^{-1} \\
\text{Stat.} & = 7, 8 \text{ TeV} \\
\text{Syst.} & = 4.5, 20.3 \text{ fb}^{-1} \\
\text{SM} & = 45 \text{ fb}^{-1} \\
\end{align*} \]
Modelling of $t\bar{t}$ is crucial to the analysis, $t\bar{t} + \text{HF}$ has large theory uncertainty

- Split into $t\bar{t} + \text{light}$, $t\bar{t} + \geq 1c$, $t\bar{t} + \geq 1b$
  - Further split $t\bar{t} + \geq 1b$ by number of additional $b$-hadrons in jets
- Nominal $t\bar{t}$ sample uses 5FS prediction
  - Use dedicated Sherpa 4FS $t\bar{t} + b\bar{b}$ prediction to improve modelling
    - Both additional $b$-quarks to NLO precision in QCD
    - Takes $b$-quark mass into account
  - Reweight relative $t\bar{t} + \geq 1b$ subcomponents to 4FS values
### Systematic Source Description

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Description</th>
<th>$t\bar{t}$ categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ cross-section</td>
<td>Up or down by 6%</td>
<td>All, correlated</td>
</tr>
<tr>
<td>$k(t\bar{t} + \geq 1c)$</td>
<td>Free-floating $t\bar{t} + \geq 1c$ normalization</td>
<td>$t\bar{t} + \geq 1c$</td>
</tr>
<tr>
<td>$k(t\bar{t} + \geq 1b)$</td>
<td>Free-floating $t\bar{t} + \geq 1b$ normalization</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>SHERPA5F vs. nominal</td>
<td>Related to the choice of NLO event generator</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>PS &amp; hadronization</td>
<td>POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>ISR / FSR</td>
<td>Variations of $\mu_R$, $\mu_F$, $h_{damp}$ and A14 Var3c parameters</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ ME vs. inclusive</td>
<td>MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)</td>
<td>$t\bar{t} + \geq 1c$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ SHERPA4F vs. nominal</td>
<td>Comparison of $t\bar{t} + bb$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ renorm. scale</td>
<td>Up or down by a factor of two</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ resumm. scale</td>
<td>Vary $\mu_Q$ from $H_T/2$ to $\mu_{CMMPS}$</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ global scales</td>
<td>Set $\mu_Q$, $\mu_R$, and $\mu_F$ to $\mu_{CMMPS}$</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ shower recoil scheme</td>
<td>Alternative model scheme</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ PDF (MSTW)</td>
<td>MSTW vs. CT10</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ PDF (NNPDF)</td>
<td>NNPDF vs. CT10</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ UE</td>
<td>Alternative set of tuned parameters for the underlying event</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ MPI</td>
<td>Up or down by 50%</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 3b$ normalization</td>
<td>Up or down by 50%</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
</tbody>
</table>
$t\bar{t}H (H \rightarrow b\bar{b})$ - Impact of Systematic Uncertainties

- Analysis is currently systematically limited
- Largest uncertainties from $t\bar{t} + HF$ modelling
- Also notable impact:
  - Limited MC stats.
  - Flavour tagging
  - Jet energy scale and resolution
- Large number of constrained two-point systematics
Reco BDT  Exploits correlations within each combination
Reco BDT  Provides jet assignments based on $t\bar{t}H (H \rightarrow b\bar{b})$
LHD  Combines all combinations together into one discriminant
LHD+MEM  Calculate both signal and background likelihoods
MEM  Calculates discriminant at parton level using 4-vectors
Looking at three signal regions post fit

- $t\bar{t}H$ shown for extracted signal strength $\mu = 0.84^{+0.64}_{-0.61}$
- Showing two most signal enriched regions and boosted signal region

See good post-fit agreement between data and simulation in all regions
**Channel Selection criteria**

**Common**
- \( N_{\text{jets}} \geq 2 \) and \( N_{b\text{-jets}} \geq 1 \)

**2\ell SS**
- Two very tight light leptons with \( p_T > 20 \) GeV
- Same-charge light leptons
- Zero medium \( \tau_{\text{had}} \) candidates
- \( N_{\text{jets}} \geq 4 \) and \( N_{b\text{-jets}} < 3 \)

**3\ell**
- Three light leptons with \( p_T > 10 \) GeV; sum of light-lepton charges \( \pm 1 \)
- Two same-charge leptons must be very tight and have \( p_T > 15 \) GeV
- The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT
- Zero medium \( \tau_{\text{had}} \) candidates
- \( m(\ell^+\ell^-) > 12 \) GeV and \( |m(\ell^+\ell^-) - 91.2 \) GeV| > 10 GeV for all SFOC pairs
- \( m(3\ell) > 125 \) GeV > 5 GeV

**4\ell**
- Four light leptons; sum of light-lepton charges 0
- Third and fourth leading leptons must be tight
- \( m(\ell^+\ell^-) > 12 \) GeV and \( |m(\ell^+\ell^-) - 91.2 \) GeV| > 10 GeV for all SFOC pairs
- \( m(4\ell) > 125 \) GeV > 5 GeV
- Split 2 categories: \( Z \)-depleted (0 SFOC pairs) and \( Z \)-enriched (2 or 4 SFOC pairs)

**1\ell + 2\tau_{\text{had}}**
- One tight light lepton with \( p_T > 27 \) GeV
- Two medium \( \tau_{\text{had}} \) candidates of opposite charge, at least one being tight
- \( N_{\text{jets}} \geq 3 \)

**2\ell SS + 1\tau_{\text{had}}**
- Two very tight light leptons with \( p_T > 15 \) GeV
- Same-charge light leptons
- One medium \( \tau_{\text{had}} \) candidate, with charge opposite to that of the light leptons
- \( N_{\text{jets}} \geq 4 \)
- \( |m(ee) - 91.2 \) GeV| > 10 GeV for ee events

**2\ell OS + 1\tau_{\text{had}}**
- Two loose and isolated light leptons with \( p_T > 25, 15 \) GeV
- One medium \( \tau_{\text{had}} \) candidate
- Opposite-charge light leptons
- One medium \( \tau_{\text{had}} \) candidate
- \( m(\ell^+\ell^-) > 12 \) GeV and \( |m(\ell^+\ell^-) - 91.2 \) GeV| > 10 GeV for the SFOC pair
- \( N_{\text{jets}} \geq 3 \)

**3\ell + 1\tau_{\text{had}}**
- 3\ell selection, except:
- One medium \( \tau_{\text{had}} \) candidate, with charge opposite to the total charge of the light leptons
- The two same-charge light leptons must be tight and have \( p_T > 10 \) GeV
- The opposite-charge light lepton must be loose and isolated
### $t\bar{t}H$ ML - BDTs

<table>
<thead>
<tr>
<th>Light lepton</th>
<th>2$\ell$SS</th>
<th>3$\ell$</th>
<th>4$\ell$</th>
<th>1$\ell$+2$\tau_{\text{had}}$</th>
<th>2$\ell$SS+1$\tau_{\text{had}}$</th>
<th>2$\ell$OS+1$\tau_{\text{had}}$</th>
<th>3$\ell$+1$\tau_{\text{had}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\text{had}}$</td>
<td>2T*</td>
<td>1L*, 2T*</td>
<td>2L, 2T</td>
<td>1T</td>
<td>2T*</td>
<td>2L†</td>
<td>1L†, 2T</td>
</tr>
<tr>
<td>N$<em>{\text{jets}}$, N$</em>{b}$-jets</td>
<td>≥ 4, = 1, 2</td>
<td>≥ 2, ≥ 1</td>
<td>≥ 2, ≥ 1</td>
<td>≥ 3, ≥ 1</td>
<td>≥ 4, ≥ 1</td>
<td>≥ 3, ≥ 1</td>
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<td>Uncertainty Source</td>
<td>$\Delta \mu$</td>
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<tr>
<td>$t\bar{t}H$ modeling (cross section)</td>
<td>+0.20</td>
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<tr>
<td>Jet energy scale and resolution</td>
<td>+0.18</td>
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<td>Non-prompt light-lepton estimates</td>
<td>+0.15</td>
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<tr>
<td>Jet flavor tagging and $\tau_{\text{had}}$ identification</td>
<td>+0.11</td>
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<tr>
<td>$t\bar{t}W$ modeling</td>
<td>+0.10</td>
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<tr>
<td>$t\bar{t}Z$ modeling</td>
<td>+0.08</td>
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<tr>
<td>Other background modeling</td>
<td>+0.08</td>
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<tr>
<td>Luminosity</td>
<td>+0.08</td>
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<tr>
<td>$t\bar{t}H$ modeling (acceptance)</td>
<td>+0.08</td>
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<tr>
<td>Fake $\tau_{\text{had}}$ estimates</td>
<td>+0.07</td>
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<td>Other experimental uncertainties</td>
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<td>Simulation sample size</td>
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<td>Charge misassignment</td>
<td>+0.01</td>
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<td>Total systematic uncertainty</td>
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**Pre-fit impact on $\mu$:**
- $\theta=\bar{\theta}+\Delta \theta$
- $\theta=\bar{\theta}-\Delta \theta$

**Post-fit impact on $\mu$:**
- $\theta=\bar{\theta}+\Delta \theta$
- $\theta=\bar{\theta}-\Delta \theta$

**Nuis. Param. Pull**

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- $t\bar{t}H$ cross section (scale variations)
- Jet energy scale (pileup subtraction)
- Luminosity
- Jet energy scale (flavor comp. 2/$SS$
- Jet energy scale variation 1
- $t\bar{t}W$ cross section (scale variations)
- $t\bar{t}Z$ cross section (scale variations)
- $\tau_{\text{had}}$ identification
- $t\bar{t}H$ cross section (PDF)
- $t\bar{t}H$ modeling (shower tune)
- Flavor tagging c-jet/$\tau_{\text{had}}$
- rare top decay cross section
- 3/$\tau$ Non-prompt closure
- $t\bar{t}W$ modeling (generator)
- Non-prompt stat. in 4th bin of 3/$\tau$ SR

Johnny Raine (UniGe)  
8th August, 2018  
Vietnam 2018
$t\bar{t}H (H \rightarrow \gamma\gamma)$ - Unweighted $m_{\gamma\gamma}$

![Graph showing data, continuum background, total background, and signal plus background. The graph plots events per 2.5 GeV bin against $m_{\gamma\gamma}$ in GeV. The data shows a peak around $m_{\gamma\gamma} = 125.09$ GeV, consistent with the Higgs boson mass. The ATLAS collaboration notes that the integrated luminosity is $79.8 \text{ fb}^{-1}$ at $\sqrt{s} = 13$ TeV.]
$t\bar{t}H (H \rightarrow \gamma\gamma)$ - Unweighted $m_{\gamma\gamma}$

- BDT trained to select three jets to form hadronic top
- Does not enter the analysis
- Top mass reconstructed in bins with highest S/B
- Excess in events around top mass consistent with $t\bar{t}H$