Searching for $t\bar{t}H \ (H \rightarrow b\bar{b})$ with ATLAS

RAL Department Seminar

Johnny Raine (Université de Genève)

16$^{th}$ May, 2018
Aim to give an overview of the search for $t\bar{t}H$ production with the ATLAS detector
- Focus on the $H \rightarrow b\bar{b}$ channel
- Describe the full analysis strategy
- Present the results and current status

Analysis presented uses 32.1 fb$^{-1}$ dataset of $pp$ collisions
- Paper submitted to PRD
Introduction

Higgs boson

- Discovered in 2012 by ATLAS and CMS collaborations
  - The last piece of the SM to be found
  - Its mass is unconstrained in the SM
- Want to measure as many properties of the particle as possible
  - Mass, charge, width, CP-nature...
  - But also, how it couples to other particles
  - Coupling strengths predicted by SM given Higgs mass
  - Currently all measurements are consistent with SM
Bosons

- Higgs coupling to all Bosons has been observed
- Directly to $W$ and $Z$ bosons
- Indirectly to $\gamma$ and gluons through loop processes
  - $\gamma\gamma$ dominated by $W$ bosons in the loop, top contributes
  - gluon loop dominated by top, small contribution from $b$-quarks

\[ g \rightarrow t/b \rightarrow H \rightarrow W/t/b \rightarrow \gamma \]
Introduction
Higgs couplings

Bosons

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- Directly to $W$ and $Z$ bosons
- Indirectly to $\gamma$ and gluons through loop processes
  - $\gamma\gamma$ dominated by $W$ bosons in the loop, top contributes
  - gluon loop dominated by top, small contribution from $b$-quarks

Fermions

- Less success with measuring the coupling to fermions
- Only direct observation of one Higgs-fermiom coupling: $H \rightarrow \tau\tau$
- Only evidence for $H \rightarrow b\bar{b}$ decay from ATLAS and CMS
- Top-Higgs coupling inferred through loop processes
Introduction
Higgs couplings

- Two areas to probe for Higgs couplings
  - In Higgs production modes and in decay channels
  - Additionally of interest is the Higgs self coupling (di-Higgs searches)

- Shown here is ggF production with $H \rightarrow ZZ$ decay
  - Production dominated by coupling to top $y_t$ and $b$-quarks $y_b$
  - Decay has direct coupling to $Z$ boson
Why $t\bar{t}H (H \rightarrow b\bar{b})$?

Direct measurement of the two largest Higgs fermion couplings

- $t\bar{t}H$:
  - Direct measurement of $y_t$
  - $y_t$ can probe scale of new physics
  - One of four main Higgs production mechanisms at LHC

- $H \rightarrow b\bar{b}$
  - Largest Higgs BR (58%)
  - In ggF, dominated by multijet background
  - S/B improved by additional final state objects ($VH$ and $t\bar{t}H$ production)
  - Only evidence from $VH(b\bar{b})$
Search for $t\bar{t}H (H \rightarrow b\bar{b})$
Analysis Overview

- Large BR but dominated by background from $t\bar{t}+\text{jets}$ events
  - $t\bar{t}H (H \rightarrow b\bar{b})$ has same final state objects as $t\bar{t} + b\bar{b}$ production
  - Cross section is $\sim 2$ orders magnitude larger than signal ($\sigma_{t\bar{t}H} = 0.5$ pb at $\sqrt{s} = 13$ TeV)

- Large focus of analysis on separating signal from background
  - Event selection and categorisation
  - Multivariate techniques (Reconstruction and Classification)

- Controlling the background modelling and systematic uncertainties
  - The dominant $t\bar{t} + \text{jets}$ background has large systematic uncertainties
  - Perform a simultaneous profile likelihood fit on signal and control regions

- Analysis is split into four steps:
  - Event selection, which split into channels based on lepton number
  - Event categorisation, performed in each channel
  - Reconstruction and Classification
  - Signal strength extraction
Background Modelling

- Search is dominated by $t\bar{t} + \text{jets}$ background
  - Split into $t\bar{t} + \geq 1b$, $t\bar{t} + \geq 1c$ and $t\bar{t} + \text{light}$
  - Defined by matching of $b/c$-hadrons to additional jets at particle level
- $t\bar{t} + b\bar{b}$ has same final state as $t\bar{t}H (H \rightarrow b\bar{b})$ signal
  - $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$ production not well understood
- Large number of systematic uncertainties cover $t\bar{t} + \text{HF}$ modelling
  - Covering choice of generator, parton shower, 3/4 vs 5FS PDFs
  - Free float normalisation of $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$ in the fit
- In order to improve the $t\bar{t} + \geq 1b$ modelling, nominal sample has individual $t\bar{t} + \geq 1b$ components adjusted to match dedicated $t\bar{t} + b\bar{b}$ sample produced to NLO precision using 4FS PDF
Event Selection and Categorisation
Event Selection and Categorisation

Objects in our Events

- From our signal/background:
  - Four $b$-quarks
  - Two $W$-bosons
- $W^\pm$ decays to $\ell\nu$ or $q\bar{q}$
  - Always require at least one lepton
  - Provides clean trigger signature
  - Two channels: $1\ell$ and $2\ell$

- Detector doesn’t see $b$-quarks
  - Hadronisation and parton shower
  - Collimated shower of particles: Jet reconstruction
  - Attempt to identify jets originating from $b$-quarks ($b$-jets)

---

1 ATLAS cannot save all events from collisions. Require triggers to decide whether to save an interesting event
Event Selection and Categorisation

*b*-tagging

- Jets constructed by grouping energy deposits in the detector (clusters)
  - Use anti-$k_t$ algorithm with $\Delta R = 0.4$
- Exploiting properties of $B$-hadrons to identify $b$-jets
  - Long lifetime $\rightarrow$ flight path in detector
  - Large impact parameter of tracks matched to a secondary vertex
- Three types of algorithms to exploit
  - Impact parameter based
  - Secondary vertex reconstruction
  - Topological decay reconstruction
- Output variables are combined into a single discriminant
Event Selection and Categorisation

$b$-tagging

- Boosted Decision Tree to combine multiple input variables
  - Separate $b$-jets from $c$- and light-flavour jets
  - Background is 80% LF, 20% $c$-jet
- Kinematic properties are also included in the training
  - Reweight the distributions to have no kinematic differences
  - But can exploit underlying correlations with other inputs
- Four $b$-tagging efficiency working points
  - 60%, 70%, 77% and 85% $b$-efficiency
  - Define $b$-tagged jets using one WP
Event Selection and Categorisation

*b-tagging*

- Boosted Decision Tree to combine multiple input variables
  - Separate $b$-jets from $c$- and light-flavour jets
  - Background is 80% LF, 20% $c$-jet
- Kinematic properties are also included in the training
  - Reweight the distributions to have no kinematic differences
  - But can exploit underlying correlations with other inputs
- Four $b$-tagging efficiency working points
  - 60%, 70%, 77% and 85% $b$-efficiency
  - Define $b$-tagged jets using one WP
  - OR use all working points together
Event Selection
Pre-selection

- In the final state expect six (four) b-jets in the $1\ell$ ($2\ell$) channels
  - Would select four b-jets at the tightest WP
  - Open up the acceptance to take into account detector efficiencies
  - A $b$-quark could be out of the acceptance of the detector/mistagged
    - Require $\geq5$ ($\geq3$) jets and reduced $b$-tag requirements in preselection
  - Use jet multiplicity and $b$-tag working points to define regions

- Additionally: consider a “Boosted” topology in $1\ell$ channel
  - High $p_T$ Higgs boson/top quark
  - Jets from decay products have significant overlap, form one fat jat
Event Categorisation

Overview

- Two methods used to categorise events
  - i. Background based categorisation (resolved events)
  - ii. Top and Higgs candidate large jet tagging (boosted events)
- Regions are used to define control regions and signal regions
  - Signal regions are enriched in $t\bar{t}H (H \rightarrow b\bar{b})$ signal
  - Control regions are all other regions
  - Multivariate techniques are used in signal regions to improve sensitivity of the analysis
Event Categorisation

Overview

Resolved Categorisation

- Start with initial loose preselection of events, consistent with $t\bar{t} + X$
- Use jet info to define regions enriched in different $t\bar{t} + \text{jets}$ composition
  - Split events by jet multiplicity, use $b$-tag WPs of up to four jets

Boosted Categorisation

- Select events with objects corresponding to $t\bar{t}H (H \rightarrow b\bar{b})$ events with a boosted Higgs and top
  - Require two large jets (anti-$k_t$ with $\Delta R = 1.0$)
    - Tag one as a top candidate
    - Tag the other as a Higgs candidate
- All events go into the boosted region in case of overlap with resolved
Event Categorisation

Boosted

- Only performed in single lepton channel
- Reduces combinatorics of final state objects
- Selection:
  - $\geq 5$ small jets, $\geq 2$ reclustered\(^1\) large jets
  - $\geq 1$ jet tagged@85\% WP outside large jets
  - $\geq 1$ top candidate, $\geq 1$ Higgs candidate

<table>
<thead>
<tr>
<th>$p_T$ [GeV]</th>
<th>Top</th>
<th>Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent jets</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tagged @ 85%</td>
<td>$\equiv 1$</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^1\) Reclustered jets are reconstructed using the anti-$k_t$ algorithm but taking smaller radius jets as inputs instead of clusters
Event Categorisation

Resolved

▶ Each jet in the event is labelled by the tightest $b$-tag WP it passes
▶ Separate events into bins of the four jet WPs ($\text{jet}_1, \text{jet}_2, \text{jet}_3, \text{jet}_4$)
Event Categorisation

Resolved

- Each jet in the event is labelled by the tightest $b$-tag WP it passes
- Separate events into bins of the four jet WPs ($\text{jet}_1, \text{jet}_2, \text{jet}_3, \text{jet}_4$)
  - The tighter the WPs the more signal and $t\bar{t} + b\bar{b}$ enriched the bin

$$60\% \ 60\% \ 60\% \ 60\% = (60, 60, 60, 60) \quad (t\bar{t}+ \geq 2b)$$
Event Categorisation

Resolved

- Each jet in the event is labelled by the tightest $b$-tag WP it passes
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  - The tighter the WPs the more signal and $t\bar{t} + b\bar{b}$ enriched the bin
  - Bins with looser jets will be enriched in $t\bar{t} + \geq 1c$ and $t\bar{t} + \text{light}$

\[
\begin{align*}
60\% & \quad 60\% & \quad 60\% & \quad 60\% & = (60,60,60,60) & (t\bar{t}+ \geq 2b) \\
60\% & \quad 70\% & \quad 60\% & \quad 85\% & \quad 100\% & = (60,60,70,85) & (t\bar{t}+ \geq 1c)
\end{align*}
\]
Event Categorisation
Resolved

- Each jet in the event is labelled by the tightest $b$-tag WP it passes
- Separate events into bins of the four jet WPs ($\text{jet}_1, \text{jet}_2, \text{jet}_3, \text{jet}_4$)
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  - Bins with looser jets will be enriched in $t\bar{t}+\geq 1c$ and $t\bar{t} + \text{light}$
    
    | 60% | 60% | 60% | 60% |
    |-----|-----|-----|-----|
    | 60% | 70% | 60% | 85% | 100% |

    $= (60,60,60,60)$ \hspace{1cm} ($t\bar{t}+ \geq 2b$)
    $= (60,60,70,85)$ \hspace{1cm} ($t\bar{t}+\geq 1c$)

- Each bin will have a different background composition
  - Combine bins with similar backgrounds to form regions
  - Finer $t\bar{t}+\geq 1b$ categorisation using number of additional $b$-hadrons
  - e.g. Merge all bins with more than 60% $t\bar{t}+ \geq 2b$
    - In $2\ell$ events with $\geq4j$: $(60,60,60,60)$ and $(60,60,60,70)$ bins
Event Categorisation
Resolved

- Using this method more freedom to have regions enriched in different backgrounds
  - Help control modelling of individual processes
- Due to shared final state, enriched $t\bar{t} + b\bar{b}$ regions are natural signal regions
- In total have 3 (5) signal regions and 4 (6) control regions in resolved $2\ell$ ($1\ell$)
- Can represent binning on 2D plot with $y = (\text{jet}_1, \text{jet}_2)$ and $x = (\text{jet}_3, \text{jet}_4)$
  - Convention uses $b$-tag discriminant bin instead of WP
  - 5=60%, 4=70% … 1=100% (untagged)
Event Categorisation
Graphical Representation - \(2\ell\) resolved

![Graphical Representation](image.png)
Event Categorisation

Graphical Representation - $1\ell$ resolved

(1st, 2nd) jet
b-tagging discriminant

(3, 3) (4, 3) (5, 3) (4, 4) (5, 4) (5, 5)

(3rd, 4th) jet
b-tagging discriminant

$1\ell$ resolved

SR

SR

CR

t $\bar{t}$ + b

CR

t $\bar{t}$ + light

(3rd, 4th) jet

(1st, 2nd) jet

(3, 3) (4, 3) (5, 3) (4, 4) (5, 4) (5, 5)

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19 regions in total, of which 9 are signal regions.

Boosted region is classed as a signal region.

- **1ℓ channel**

- **2ℓ channel**
19 regions in total, of which 9 are signal regions
- Boosted region is classed as a signal region
Reconstruction and Classification
Analysis Strategy
Overview

- Perform a binned profile likelihood fit simultaneously across all regions
  - In the signal regions want to enhance sensitivity to $t\bar{t}H$ events
  - Use the control regions to help handle the $t\bar{t} + \text{jets}$ background
- Use an MVA discriminant in all signal regions
  - Two stage strategy employed - Reconstruction $\rightarrow$ Classification
- In control regions use either a single bin or scalar sum of jet $p_T$ ($H_T^{\text{had}}$)
  - $H_T^{\text{had}}$ only used in $t\bar{t} + c$ CRs in $1\ell$ regions
  - Required additional control over $t\bar{t} + \geq 1c$ modelling
Two Stage MVA
1. Reconstruction

- Solve object combinatorics to reconstruct event hard scatter
  - Match jets/leptons to the partons in $t\bar{t}H (H \rightarrow b\bar{b})/t\bar{t} + b\bar{b}$

- Three complimentary techniques used
  - i. Reconstruction BDT
  - ii. Likelihood discriminant
  - iii. Matrix Element Method

- From each can construct variables with strong discrimination power

- Note: No explicit reconstruction in the Boosted region
  - Use the tagged Higgs candidate from event selection
Two Stage MVA

1. Reconstruction - Reconstruction BDT

- Train a BDT to assign jets to the partons in $t\bar{t}H (H \rightarrow b\bar{b})$ hard scatter
  - Discriminates against combinatoric background
  - Use invariant masses and angular separations of jets/leptons
  - Evaluate on all events to choose jet matching
- Get a most $t\bar{t}H$-like jet-parton matching per event
  - Use BDT output score as a discriminant
  - Signal events more likely to have higher output score
  - Reconstruct object properties from jet assignment - Higgs mass
- Method used in all resolved signal regions
Two Stage MVA

1. Reconstruction

### Likelihood Discriminant

- Only used in $1\ell$ resolved signal regions
- Probability of an event to be signal or background ($t\bar{t} + b$ or $t\bar{t} + b\bar{b}$)
  - 1D PDFs constructed for inv. masses and angular distributions
  - Probabilities calculated as weighted product of all 1D PDFs
  - Weighted average of all possible combinations per event
- Final discriminant is a likelihood ratio of the sig and bkg probabilities

### Matrix Element Method

- Only performed in the most signal enriched $1\ell$ signal region
- Uses the four vector information of all jets and leptons, and the MET
- Signal and background hypothesis testing performed at parton level
- Final discriminant log of sig and bkg likelihood ratio
Two Stage MVA

1. Reconstruction

**Reco BDT**
- Exploits correlations within each combination
- 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
Two Stage MVA
2. Classification

- Construct discriminants in each signal region to separate $t\bar{t}H$ from $t\bar{t}$
- Combine multiple variables with moderate separation power
  - Most powerful variables come from the reconstruction methods
- BDT optimised in each signal region
- Cross-validation performed to mitigate problems from overtraining
- Binning optimised for final significance in the fit
Two Stage MVA

2. Classification

Exanmple Input Variables

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Event Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Reco discriminants</td>
<td>▶ From event $E-\vec{p}$ tensor (Aplanarity, Sphericity)</td>
</tr>
<tr>
<td>▶ Object properties (i.e. Higgs mass) from reco BDT</td>
<td>▶ Fox-Wolfram moments</td>
</tr>
<tr>
<td>▶ Boosted Higgs/top properties</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Event</th>
<th>Object Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ nJets above $p_T$ threshold</td>
<td>▶ Properties of a $(b)$-jet pair passing criteria</td>
</tr>
<tr>
<td>▶ Large Jet substructure</td>
<td>▶ $\Delta \eta_{bb}^{Max}$, $M_{jj}^{Minp_T}$</td>
</tr>
</tbody>
</table>
Analysis Strategy

Event Reconstruction and Classification

Two Stage MVA

Final Discriminant

- Most signal enriched region in each selection (2\(\ell\), 1\(\ell\) resolved/boosted)
- Regions shown before performing the fit
  - Red is \(t\bar{t}H\) assuming SM xsec

### ATLAS

- \(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
- Dilepton
- SR\(^{26}\)
- Pre-Fit

- Data
- \(t\bar{t} + \text{light}\)
- \(t\bar{t} + \geq 1c\)
- \(t\bar{t} + \geq 1b\)
- \(t\bar{t} + V\)
- Non-\(t\)
- Total unc.
- \(t\bar{t}H\) (norm)

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- \(t\bar{t} + \geq 1b\)
- \(t\bar{t} + V\)
- Non-\(t\)
- Total unc.
- \(t\bar{t}H\) (norm)
Results
Perform binned profile likelihood fit across all bins and regions simultaneously
   ▶ No distinction made between Signal and Control regions in the fit
Parameter of interest is $t\bar{t}H$ signal strength $\mu_{t\bar{t}H}$
   ▶ Defined as $\mu_{t\bar{t}H} = \frac{\sigma_{t\bar{t}H}^{obs}}{\sigma_{t\bar{t}H}^{SM}}$
Large number of nuisance parameters covering modelling and detector systematic uncertainties
   ▶ Free-floating $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ normalisation factors
Results

- Individual channel assessed using decorrelated signal strength
  - Still fit all regions simultaneously
- $t\bar{t}H$ has an observed (expected) significance of $1.6\sigma$ ($1.8\sigma$)
- Exclude $\mu > 2.0$ at 95% CL
Results

Regions Summary

Pre-Fit

Post-Fit

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Let's revisit the three regions shown before

$t\bar{t}H$ shown for extracted signal strength $\mu = 0.84^{+0.64}_{-0.61}$
Results
Impact of Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}+ \geq 1b$ modelling</td>
<td>+0.46 -0.46</td>
</tr>
<tr>
<td>Background-model stat. unc.</td>
<td>+0.29 -0.31</td>
</tr>
<tr>
<td>$b$-tagging efficiency and mis-tag rates</td>
<td>+0.16 -0.16</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.14 -0.14</td>
</tr>
<tr>
<td>$t\bar{t}H$ modelling</td>
<td>+0.22 -0.05</td>
</tr>
<tr>
<td>$t\bar{t}+ \geq 1c$ modelling</td>
<td>+0.09 -0.11</td>
</tr>
<tr>
<td>JVT, pileup modelling</td>
<td>+0.03 -0.05</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>+0.08 -0.08</td>
</tr>
<tr>
<td>$t\bar{t}$ + light modelling</td>
<td>+0.06 -0.03</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.03 -0.02</td>
</tr>
<tr>
<td>Light lepton ($e, \mu$) id., isolation, trigger</td>
<td>+0.03 -0.04</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.57 -0.54</td>
</tr>
<tr>
<td>$t\bar{t}+ \geq 1b$ normalisation</td>
<td>+0.09 -0.10</td>
</tr>
<tr>
<td>$t\bar{t}+ \geq 1c$ normalisation</td>
<td>+0.02 -0.03</td>
</tr>
<tr>
<td>Intrinsic statistical uncertainty</td>
<td>+0.21 -0.20</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>+0.29 -0.29</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+0.64 -0.61</td>
</tr>
</tbody>
</table>

- Analysis is currently systematically limited
- Largest uncertainties from $t\bar{t} + HF$ modelling
- Also notable impact:
  - Bkg modelling stats.
  - Flavour tagging
  - Jet energy scale and resolution
Results
Impact of Systematic Uncertainties

- Analysis is currently systematically limited
- Largest uncertainties from $t\bar{t} + HF$ modelling
- Also notable impact:
  - Bkg modelling stats.
  - Flavour tagging
  - Jet energy scale and resolution
- Large number of constrained two-point systematics
$t\bar{t}H$ Combination
Results

$t\bar{t}H$ Combination

- $t\bar{t}H$ ($H \rightarrow b\bar{b}$) is just one of several searches in ATLAS for $t\bar{t}H$
- Other searches are optimised for other Higgs decay modes
  - $t\bar{t}H$ multileptons: $H \rightarrow WW^*/ZZ^*/\tau\tau$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow 4\ell$

- All analyses have been performed using same 36.1 fb$^{-1}$ dataset
- A combined fit over all channels has also been performed
**t\bar{t}H multileptons**

- 8 distinct signal regions targeting different decay modes
- Dominant backgrounds from $t\bar{t} + V$, $t\bar{t}$, fake and non-prompt leptons
  - Use a BDT to suppress non-prompt leptons
  - MVA discriminants used in five signal regions
- Wide range of S/B, from a few percent to >40%

**t\bar{t}H resonant searches**

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are $t\bar{t}H$ enriched regions in inclusive searches
  - Only use $t\bar{t}H$ enriched regions
- $H \rightarrow \gamma\gamma$: Cut based and BDT selections to separate signal from ggF and multijet backgrounds
- $H \rightarrow ZZ^* \rightarrow 4\ell$: Very pure cut and count, expected < 0.5 events
Combining all $t\bar{t}H$ searches

Non-$t\bar{t}H$ production modes set to SM values

Almost all detector and signal and background uncertainties treated as correlated

Best fit value of

- $\mu_{t\bar{t}H} = 1.2^{+0.19}_{-0.23} (stat) ^{+0.21}_{-0.3} (syst)$
- $\sigma_{t\bar{t}H} = 590^{+160}_{-150} \text{ fb}^{-1}$

Combined observed (expected) significance of 4.2 $\sigma$ (3.8$\sigma$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Best-fit $\mu_{t\bar{t}H}$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>Multilepton</td>
<td>$1.6 ^{+0.5}_{-0.4}$</td>
<td>$1.0 ^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$0.8 ^{+0.6}_{-0.6}$</td>
<td>$1.0 ^{+0.6}_{-0.6}$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$0.6 ^{+0.7}_{-0.6}$</td>
<td>$1.0 ^{+0.8}_{-0.6}$</td>
</tr>
<tr>
<td>$H \rightarrow 4\ell$</td>
<td>$&lt; 1.9$</td>
<td>$1.0 ^{+3.2}_{-1.0}$</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.2 ^{+0.3}_{-0.3}$</td>
<td>$1.0 ^{+0.3}_{-0.3}$</td>
</tr>
</tbody>
</table>
Results
	$t\bar{t}H$ Combination - Interpretations

- Wide range of Higgs couplings probed in the combination
- Using the kappa-parameterisation, scale the Higgs-couplings of particles (or groups of particles) by a factor $\kappa_i$
  - Look at coupling of Higgs boson to fermions $\kappa_F$ and vector bosons $\kappa_V$
  - Couplings to gluons and photons comes from loop processes

- Consistent with Standard Model
Conclusion
Latest results from ATLAS for search for $t\bar{t}H (H \rightarrow b\bar{b})$ including combination with other channels

Very challenging analysis with heavy use of multivariate techniques to enhance sensitivity

- Also makes full use of flavour tagging in region definitions to help control $t\bar{t} + \text{jets}$ backgrounds

$t\bar{t}H (H \rightarrow b\bar{b})$ is currently systematically dominated

- Observed (expected) significance of $1.6\sigma (1.8\sigma)$
- Consistent with SM and B-Only hypotheses

Evidence for $t\bar{t}H$ with 36.1 fb$^{-1}$ ATLAS Run 2 data in combination
Additional data collected in 2017 could push combination above $5\sigma$

Potential $H \rightarrow b\bar{b}$ combination to aim for $5\sigma$ using 2017 data
- Combining $VH$, $t\bar{t}H$ and VBF searches targeting $b\bar{b}$
- Currently $3\sigma$ from $VH(b\bar{b})$ search

However, further understanding of background modelling required for $t\bar{t}H (H \rightarrow b\bar{b})$ search
Backup
Region Composition
Detailed

ATLAS
\( \sqrt{s} = 13 \text{ TeV} \)

Single Lepton

\[
\begin{align*}
\text{CR}_{\text{lt}, \text{light}}^{(5)} & \quad \text{CR}_{\text{lt}, \geq 1c}^{(5)} \quad \text{CR}_{\text{lt}, \geq 3b}^{(5)} \\
\text{SR}_{1}^{(5)} & \quad \text{SR}_{2}^{(5)} \quad \text{SR}_{\text{boosted}}^{(5)} \\
\end{align*}
\]

Dilepton

\[
\begin{align*}
\text{CR}_{\text{lt}, \text{light}}^{(3)} & \quad \text{CR}_{\text{lt}, \geq 1c}^{(3)} \quad \text{CR}_{\text{lt}, \geq 3b}^{(3)} \\
\text{SR}_{1}^{(3)} & \quad \text{SR}_{2}^{(3)} \quad \text{SR}_{\text{boosted}}^{(3)} \\
\end{align*}
\]
## Region Definitions

### Semileptonic Regions

<table>
<thead>
<tr>
<th>Region name</th>
<th>Definition</th>
<th>Region name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 6 ) jets</td>
<td>( &gt; 60% \ t \bar{t} + \geq 2b )</td>
<td>( \geq 5 ) jets</td>
<td>( &gt; 60% \ t \bar{t} + \geq 2b )</td>
</tr>
<tr>
<td>( \geq 6 ) jets ( \geq 6j )</td>
<td>( &gt; 45% \ t \bar{t} + \geq 2b )</td>
<td>( \geq 5 ) jets ( \geq 5j )</td>
<td>( &gt; 20% \ t \bar{t} + \geq 2b )</td>
</tr>
<tr>
<td>( \geq 6 ) jets ( \geq 3 ) light</td>
<td>( &gt; 30% \ t \bar{t} + \geq 2b )</td>
<td>( \geq 5 ) jets ( \geq 3 ) light</td>
<td>( &gt; 30% \ t \bar{t} + \geq 2b )</td>
</tr>
<tr>
<td>( \geq 6 ) jets ( \geq 6j )</td>
<td>( &gt; 30% \ t \bar{t} + 1b )</td>
<td>( \geq 5 ) jets ( \geq 4j )</td>
<td>( &gt; 20% \ t \bar{t} + 1b )</td>
</tr>
<tr>
<td>( \geq 6 ) jets ( \geq 6j ) ( \geq 1c )</td>
<td>( &gt; 30% \ t \bar{t} + \geq 1c )</td>
<td>( \geq 5 ) jets ( \geq 4j ) ( \geq 1c )</td>
<td>( &gt; 20% \ t \bar{t} + \geq 1c )</td>
</tr>
<tr>
<td>( \geq 6 ) jets ( \geq 6j ) ( \geq 1c ) light</td>
<td>Remaining events</td>
<td>( \geq 5 ) jets ( \geq 4j ) ( \geq 1c ) light</td>
<td>Remaining events</td>
</tr>
</tbody>
</table>

### Dilepton Regions

<table>
<thead>
<tr>
<th>Region name</th>
<th>Definition</th>
<th>Region name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 4 ) jets</td>
<td>( &gt; 70% \ t \bar{t} + \geq 2b )</td>
<td>( \geq 3 ) jets</td>
<td>( &gt; 30% \ t \bar{t} + \geq 1b )</td>
</tr>
<tr>
<td>( \geq 4 ) jets ( \geq 4j )</td>
<td>( &gt; 1.5% \ t \bar{t}H )</td>
<td>( \geq 3 ) jets ( \geq 4j )</td>
<td>( &gt; 25% \ t \bar{t} + \geq 1c )</td>
</tr>
<tr>
<td>( \geq 4 ) jets ( \geq 4j ) ( \geq 1c ) light</td>
<td>Remaining events</td>
<td>( \geq 3 ) jets ( \geq 4j ) ( \geq 1c ) light</td>
<td>Remaining events</td>
</tr>
</tbody>
</table>
Comparing the three signal regions directly

- $t\bar{t}H$ shown post-fit for extracted signal strength $\mu = 0.84^{+0.64}_{-0.61}$