Analyses of ttH production in ATLAS

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On behalf of the ATLAS Collaboration
Higgs Couplings 2018: Tokyo
Experimental Challenge

- $t\bar{t}H$ production cross-section at $\sqrt{s} = 13$ TeV: Only $\sim 1\%$ of the total Higgs cross section
- Wide range of analyses designed to target
  - the various Higgs boson decays
  - Additional considerations to the decay of top pair (0, 1, and 2 leptons)
- Final states with many objects: jets, b-jets, e, $\mu$, hadronic $\tau$, photons
  - many experiment handles to identify events

$0.507 \text{pb} \pm 5.8\% \text{(QCD scales)} \pm 3.6\% \text{(PDF,}\alpha_s\text{)}$
Experimental Challenge

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Overview of results

**Multi-lepton**


13 TeV, 36.1 fb⁻¹

**H → bb**


13 TeV, 36.1 fb⁻¹

**H → γγ**

H → ZZ → 4ℓ


13 TeV, 79.8 fb⁻¹

**Combination**


13 TeV, 36.1 - 79.8 fb⁻¹
Multi-lepton

- **7 analysis channels** depending on e/μ and hadronic τ multiplicity
  ≥1 b-jet, 2-4 jets

- Isolation/b-tagging BDT for light lepton selection, veto on charge mis-ID BDT

- **Targeted decays:**
  \(WW^*(\rightarrow l\nu_l l\nu_{l'}), \tau\tau, ZZ^*(\rightarrow l\nu_l l\nu_{l'}qq)\)

- **Backgrounds:**
  - Irreducible: dominated by tt+V and VV
    - Taken from MC and validated in data
  - Reducible: non-prompt e/μ/τ, electron charge misidentified, photon conversions
    - Estimated from data
Multi-lepton

- **7 analysis channels** depending on $e/\mu$ and hadronic $\tau$ multiplicity
  - $\geq 1$ b-jet, 2-4 jets

- Isolation/b-tagging BDT for light lepton selection, veto on charge mis-ID BDT

- **Targeted decays:**
  - $WW^* (\rightarrow l\nu l\nu, l\nu qq), \tau\tau, ZZ^*(\rightarrow l\nu l\nu, l\nu qq)$

- **Backgrounds:**
  - Irreducible: dominated by $tt+V$ and $VV$
    - Taken from MC and validated in data
  - Reducible: non-prompt $e/\mu/\tau$, charge misidentified $e/\mu$
    - Estimated from data
## Multi-lepton: signal extraction

Dedicated MVA approaches in most channels

<table>
<thead>
<tr>
<th>Discriminant</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>Fakes and t\bar{t}V</td>
<td>2×1D BDT</td>
<td>t\bar{t}, t\bar{t}W, t\bar{t}Z, VV</td>
<td>t\bar{t}Z / -</td>
<td>t\bar{t}</td>
<td>all</td>
<td>t\bar{t}</td>
<td>-</td>
</tr>
<tr>
<td>Number of bins</td>
<td>6</td>
<td>5</td>
<td>1 / 1</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Control regions</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### ATLAS

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

**2\ell SS**

**Post-Fit**

![Histogram of 2\ell SS](image1)

**ATLAS**

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

**3\ell SR**

**Post-Fit**

![Histogram of 3\ell SR](image2)
Combined profile likelihood fit of all SRs and CRs:
- BDT discriminants in most signal regions
- Control regions validate irreducible backgrounds

Dominant uncertainties on $\mu_{ttH}$:
- $ttH$ cross-section (+0.20 -0.09)
- Jet energy scale and resolution (+0.18 -0.15)
- Non-prompt e/\mu estimates (+0.15 -0.13)
H → bb

Analysis regions

• Di-lepton channel:
  • 2 light leptons (e, μ), ≥3 jets

• Single lepton channel:
  • 1 light lepton (e, μ), ≥5 jets

• Boosted (single-lepton) channel:
  • large-R top-like and Higgs-like jets
    (see Emma Winkel’s talk)

• Biggest challenge: large irreducible tt+HF background

![Diagram]

- Regions built using 5 b-tagging working points and Njets
H→bb: analysis regions

**lepton+jets**

Six control regions  
S/B < 1.5%

Five signal regions  
highest purity region  
S/B = 5.3%
**H→bb: signal extraction**

- **Signal extraction strategy:**
  - Intermediate MVAs aimed at signal reconstruction
    (ttH system reconstruction BDT, Likelihood discriminant, Matrix Element Method)
  - Fit performed on classification BDT output
    (inputs: reconstruction MVA, kinematics, b-tagging info)
H→bb: results

Fit: Profile likelihood fit of 10 control regions and 9 signal regions
- BDT distributions in all SRs
- $H_T$ (scalar sum of jet pT) or single bin in CRs
Free-floating $tt + \geq 1b$ and $tt + \geq 1c$ normalisation

Dominant uncertainties on $\mu_{ttH}$:
- $tt + \geq 1b$ modelling (+0.46, -0.46)
- MC statistical uncertainties (+0.29, -0.31)
- b-tagging (+0.16, -0.16)
Analysis regions
Two isolated photons + 1 b-tagged jet
- Leptonic region:
  - ≥1l (semi-leptonic top-quark decay)
- Hadronic region:
  - ≥2jets + 0 isolated leptons (hadronic top-quark decay)

Signal-enriched regions:
- 2 BDTs trained to discriminate the ttH signal from the main background:
  - γγ, tt+γγ (data in control regions)
  - other Higgs production (from simulation)
- BDT inputs: photon kinematics (pT/mγγ, η, φ), magnitude and φ of the E_Tmiss, jet and lepton 4-vectors
- Cut on BDT output to veto backgrounds
H → γγ: strategy

- 85% (97%) of ttH events are selected and 89% (43%) of background events are rejected in the Had (Lep) region.

- Remaining events are categorised into:
  - four bins in the hadronic region
  - three bins in the leptonic region
H$\to\gamma\gamma$: strategy

- Dedicated BDT trained to identify jets from same top decays
- Reconstruct the top-quark candidate mass from a triplet of jets selected by this BDT
- This BDT, and the top-candidate mass, are not directly used in the analysis
$H \rightarrow \gamma \gamma$: results

- Simultaneous unbinned fit of $m_{\gamma \gamma}$ (105-160 GeV) in all 7 categories
  - $ttH$ signal: double-sided crystal ball
  - Continuum background: smooth functions (power-law or exponential)

**Significance:** $4.1\sigma$ ($3.7\sigma$ expected)
- **Hadronic:** $3.8\sigma$ ($2.7\sigma$)
- **Leptonic:** $1.9\sigma$ ($2.5\sigma$)

Dominant uncertainties:
- Statistically dominated
- $ttH$ shower & hadronization (8%)
- Photon isolation, resolution, scale (8%)
- Jet energy scale (5%)

50% more sensitive than previous result:
- Inclusion in BDT of 4-mom information of objects (30% improvement for same luminosity)
- Improved reconstruction and selection
$H \rightarrow ZZ^* \rightarrow 4l$

3 Analysis regions

- 115 GeV < $m_{4l}$ < 130 GeV
- Hadronic-enriched region:
  - $\geq 4$ jets, $\geq 1$ b-tag, no additional light leptons
  - Split in two bins using a BDT (“Had 1”, “Had 2”)
- Leptonic-enriched region
  - $\geq 2$ jets, $\geq 1$ b-tag, $\geq 1$ additional light lepton

Major backgrounds

- $ttV$
- non-$ttH$ Higgs production modes

Extremely statistically limited:

- no events observed in signal region
- 1.1 events expected (0.6 $ttH$)
- Expected sensitivity: 1.2$\sigma$

<table>
<thead>
<tr>
<th>Bin</th>
<th>$ttH$ (signal)</th>
<th>Non-$ttH$ Higgs</th>
<th>Non-Higgs</th>
<th>Total</th>
<th>Observed Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Had 1</td>
<td>0.169(31)</td>
<td>0.021(7)</td>
<td>0.008(8)</td>
<td>0.198(33)</td>
<td>0</td>
</tr>
<tr>
<td>Had 2</td>
<td>0.216(32)</td>
<td>0.20(9)</td>
<td>0.22(12)</td>
<td>0.63(16)</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>0.253(34)</td>
<td>0</td>
</tr>
</tbody>
</table>
Overview of results

**Multi-lepton**

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$H \rightarrow \gamma \gamma$

$H \rightarrow ZZ \rightarrow 4\ell$


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**Combination**


13 TeV, 36.1 - 79.8 fb⁻¹
Combination

- Analysis inputs:
  - $b\bar{b}$, multi-lepton: 36.1 fb$^{-1}$
  - $\gamma\gamma$, $ZZ^* \rightarrow 4l$: 79.8 fb$^{-1}$
- Negligible overlap between event from different channels
- Combination details:
  - Theory uncertainties correlated
  - Experimental uncertainties largely uncorrelated
  - Other Higgs production modes fixed to SM

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated luminosity [fb$^{-1}$]</th>
<th>Obs. sign.</th>
<th>Exp. sign.</th>
</tr>
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<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>79.8</td>
<td>4.1 $\sigma$</td>
<td>3.7 $\sigma$</td>
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<td>$H \rightarrow$ multilepton</td>
<td>36.1</td>
<td>4.1 $\sigma$</td>
<td>2.8 $\sigma$</td>
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<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>36.1</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>0 $\sigma$</td>
<td>1.2 $\sigma$</td>
</tr>
<tr>
<td>Combined (13 TeV)</td>
<td>36.1−79.8</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>6.3 $\sigma$</td>
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Run 2 data alone: Observation of $ttH$!
Combination

- Analysis inputs:
  - $b\bar{b}$, multi-lepton: 36.1 fb$^{-1}$
  - $\gamma\gamma$, $ZZ^\ast \rightarrow 4l$: 79.8 fb$^{-1}$
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<th>Uncertainty source</th>
<th>$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]</th>
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<tr>
<td>Theory uncertainties (modelling)</td>
<td>11.9</td>
</tr>
<tr>
<td>$t\bar{t}$ + heavy flavour</td>
<td>9.9</td>
</tr>
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<td>$t\bar{t}H$</td>
<td>6.0</td>
</tr>
<tr>
<td>Non-$t\bar{t}H$ Higgs boson production modes</td>
<td>1.5</td>
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<td>Other background processes</td>
<td>2.2</td>
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<td>Fake leptons</td>
<td>5.2</td>
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<td>Jets, $E_T^{miss}$</td>
<td>4.9</td>
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<td>Electrons, photons</td>
<td>3.2</td>
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<td>Luminosity</td>
<td>3.0</td>
</tr>
<tr>
<td>$\tau$-lepton</td>
<td>2.5</td>
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<td>Flavour tagging</td>
<td>1.8</td>
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<td>MC statistical uncertainties</td>
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Dominant uncertainties

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A clear $ttH$ signal-like excess over the background is visible at high $S/B$. 

**ATLAS**

$\sqrt{s}=13$ TeV, 36.1 - 79.8 fb$^{-1}$

- Data
- $ttH (\mu=1.32)$
- $ttH (\mu=1)$
- Background
Observation of ttH production process:

- 6.3σ significance (5.1σ expected) with Run 1 + Run 2
- Good agreement of cross section measurement with SM
BACK UP