Observation of Higgs boson production in association with a $t\bar{t}b\bar{b}$ pair

Yasuyuki Horii, Nagoya University on behalf of the ATLAS Collaboration
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Introduction

- Top Yukawa coupling ($y_t$) contributes to the following quantum loops.
  - Higgs gluon fusion production
  - Higgs diphoton decay
- Run 1 ATLAS+CMS result: 20% precision in $y_t$ but assuming no BSM contributions in the loops.
- $ttH$ cross section measurement allows direct constraint on top Yukawa coupling.
Experimental Signatures for ttH

- Signature depends on
  - ttbar system decay:
    - 0, 1, and 2 charged leptons
  - Higgs decay: bb, WW*, ττ, ZZ*, γγ

- Four different analyses:
  - ttH with H→bb (0, 1, or 2 e/μ)
  - ttH to multilepton
targetting mostly H→WW* and ττ
  - ttH with H→γγ (0 or ≥ 1 e/μ)
  - ttH with H→ZZ*→ 4 e/μ

Smaller BR, larger S/B
## Latest Results on ttH at ATLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Data ($\sqrt{s}$, $\int Ldt$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH, $H \rightarrow \gamma\gamma$</td>
<td>13 TeV, 79.8 fb$^{-1}$</td>
<td>arXiv:1806.00425, submitted to Phys. Lett. B</td>
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</tbody>
</table>

Combination of all analyses with 36.1 fb$^{-1}$ led to 4.2$\sigma$ (3.8$\sigma$ expected) evidence.

New results on $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ with 79.8 fb$^{-1}$ improve the significance.

### Notes:
- 36.1 fb$^{-1}$: data taken in 2015-2016
- 79.8 fb$^{-1}$: data taken in 2015-2017
ttH, $H \rightarrow bb$: Analysis Strategy

Largest Higgs branching ratio, but $tt +$ heavy flavour production has large cross section and the modelling is challenging.

1 lepton and 2 lepton channels split into 9 signal regions and 10 control regions based on jet and b-jet multiplicity/quality. Pseudo-continuous b-tagging introduced; b-tagging discriminant defined for efficiency points 60%, 70%, 77%, 85%, and 100%.

Boosted Decision Tree (BDT) in each signal region used as the final discriminants for signal extraction.
Signal is extracted with binned profile likelihood fit to all signal and control regions.
Normalisations of $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$ are allowed to float in the fit.

**Signal strength $\mu = \sigma/\sigma_{SM}$**

\[
\mu = 0.84 \pm 0.29 \text{ (stat.)} \pm 0.57 \text{ (syst.)}
\]

Significance: $1.4\sigma$ ($1.6\sigma$ expected)

Main systematic uncertainties
- $t\bar{t} + \geq 1b$ background modelling
  (generator comparison Syst.): $\pm 0.46$
- Background-model Stat. Unc.: $+0.29 \quad -0.31$
**ttH, Multilepton: Analysis Strategy**

- **Combination of seven channels** with different $e/\mu$ and $\tau$ lepton multiplicity
- **BDT-based prompt $e/\mu$ selection**: $\sim 20$ rejection for $e/\mu$ from $b$ hadrons
- **Irreducible backgrounds** ($ttW$, $ttZ$, …): estimated from MC and validated in data
- **Reducible backgrounds** (non-prompt $e/\mu$ and fake $\tau_{\text{had}}$): estimated from data
- **Multivariate techniques** applied in most channels

### Diagram

- **Number of $\tau_{\text{had}}$**
  - 0: $1\ell+2\tau_{\text{had}}$
  - 1: $2\ell\text{SS}+1\tau_{\text{had}}$, $2\ell\text{OS}+1\tau_{\text{had}}$
  - 2: $3\ell+1\tau_{\text{had}}$
  - 3: $4\ell$

- **Number of light leptons**
  - 2: $2\ell\text{SS}$
  - 3: $3\ell$

### Signal Fraction [%]

- **$H \rightarrow other$**
- **$H \rightarrow \tau \tau$**
- **$H \rightarrow ZZ$**
- **$H \rightarrow WW$**

**ATLAS Simulation**

- $\sqrt{s} = 13$ TeV

### Channels

- 2lSS
- 3l SR
- 4l Z-enriched
- 4l Z-depleted
- 2lSS+1\tau_{\text{had}}
- 2lOS+1\tau_{\text{had}}
- 3l+1\tau_{\text{had}}
- 1l+2\tau_{\text{had}}
Signal is extracted with a binned profile likelihood fit across all categories including main background control region.

**Main systematic uncertainties**

- **ttH modelling (cross section):** $+0.20$ $-0.09$
- **Jet energy scale/resolution:** $+0.18$ $-0.15$
- **Non-prompt e/\mu estimates:** $+0.15$ $-0.13$

$\mu = 1.6 \pm 0.3 \text{ (stat.)} ^{+0.4}_{-0.3} \text{ (syst.)}$

**Significance:** $4.1\sigma$ ($2.8\sigma$ expected)
**ttH, H→γγ: Analysis Strategy**

**50% improvement in the sensitivity:**
new analysis method and new reconstruction software

- Categorisation based on 0/≥1 lepton events
  — hadronic and leptonic categories
- Further categorisation with XGBoost BDT
  - Inputs: 4-vector information of photons (pT/mγγ), jets, Emiss, lepton(s) (lep cat), and b-tag (had cat)
  - Training: ttH MC vs main background (γγ, ttγγ) from data control region and other background from simulation
  - 4 hadronic and 3 leptonic categories based on the BDT output
ttH, H→γγ: Result

Combined unbinned fit is applied for the seven $m_{γγ}$ distributions to extract signal (double-sided Crystal Ball function) and background (exponential or power-law)

Number of fitted ttH events: 36 $^{+12}_{-11}$

Significance: $4.1σ$ ($3.7σ$ expected)

$μ = 1.39^{+0.42}_{-0.38}$ (stat.) $^{+0.23}_{-0.17}$ (syst.)

Systematic uncertainties:
ttH parton shower model (8%), photon energy resolution (6%), …
ttH, $H \rightarrow ZZ^* \rightarrow 4l$ ($l = e$ or $\mu$)

- Extremely low rate but clean final state with high S/B rate (> 5)
- Select $H \rightarrow ZZ^* \rightarrow 4l$ candidates and define ttH-enriched category:
  - $\geq 1$ b-tagged jet
  - $\geq 4$ jets (hadronic ttbar) or
    - 1 lepton + $\geq 2$ jets (leptonic ttbar)
- BDT in hadronic category
  - Inputs: kinematic variables including matrix element discriminant (ttH vs ttV)
  - Expected significance: $1.2 \sigma$

Expect 0.6 ttH events in $115 \text{ GeV} < m_{4l} < 130 \text{ GeV}$, but observe 0 events
ttH Combination

Simultaneous fits applied to signal regions and control regions of the individual analyses. Contributions from non-ttH Higgs production fixed to the SM prediction. Correlation scheme of systematic uncertainties studied in detail.

Significance

<table>
<thead>
<tr>
<th>Obs. (Exp.)</th>
<th>13 TeV only</th>
<th>7, 8, and 13 TeV</th>
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<tbody>
<tr>
<td>1.4σ (1.6σ)</td>
<td>5.8σ (4.9σ)</td>
<td>6.3σ (5.1σ)</td>
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<tr>
<td>4.1σ (2.8σ)</td>
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<tr>
<td>4.1σ (3.7σ)</td>
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<tr>
<td>0σ (1.2σ)</td>
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Observation of ttH production!
ttH Cross Section

Cross section for $pp \rightarrow ttH$ is extracted assuming SM branching ratios.

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<thead>
<tr>
<th>Analysis</th>
<th>$ttH$ cross section [fb]</th>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$710 \pm 210$ (stat.) $^{+120}_{-90}$ (syst.)</td>
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<tr>
<td>$H \rightarrow$ multilepton</td>
<td>$790 \pm 150$ (stat.) $^{+150}_{-140}$ (syst.)</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$400 \pm^{150}_{-140}$ (stat.) $\pm 270$ (syst.)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$&lt;900$ (68% CL)</td>
</tr>
</tbody>
</table>

Combined (13 TeV): $670 \pm 90$ (stat.) $^{+110}_{-100}$ (syst.) fb

Compatible with the SM prediction: $507^{+35}_{-50}$ fb

Dominant systematic uncertainties:
- $tt +$ heavy flavour modelling (9.9%)
- $ttH$ modelling (6.0%)
- Non-prompt leptons (5.2%)
- Jets/$E_T^{miss}$ (4.9%)
Conclusion

- We have observed the $t\bar{t}H$ process.
  - Run 2: $5.8\sigma$ ($4.9\sigma$ exp.)
  - Run 2 + Run 1: $6.3\sigma$ ($5.1\sigma$ exp.)
- Cross section measurements are in agreement with SM prediction.
  - Measurement for 13 TeV:
    - $670 \pm 90$ (stat.) $^{+110}_{-100}$ (syst.) fb
  - SM prediction: $507^{+35}_{-50}$ fb

Establishment of the tree-level coupling of the Higgs boson and the top quark!