Higgs boson couplings to quarks at the ATLAS experiment

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The 27th International Workshop on Weak Interactions and Neutrinos
The Standard Model

Describes everything experimentally confirmed before 2012

Higgs sector

Yukawa coupling with new scalar (completely new interaction type)
$t\bar{t}H, H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ are important!

Higgs potential $(\mu^2 \phi^2 + \lambda \phi^4)$ (to be explored by High Lumi-LHC)

Gauge boson interaction with new scalar (new for scalar, but known for fermions)
• Higgs coupling to top quarks
• Higgs coupling to bottom quarks
• Higgs coupling to charm quarks
How to Identify b quark jets in ATLAS

- Two major information to Identify b jets
  - Impact parameters
  - Secondary vertex from B decay
ATLAS Detector upgrade: Run 1 to Run 2

- Adding a new layer of pixel detector
  - IBL = New Insertable pixel B-Layer at R=33 mm

- Light jet rejection power with vertexing algorithm increased
Higgs coupling to top quarks

• Higgs coupling to top quarks
  – Associated production with a top quark pair (ttH)

• Higgs coupling to bottom quarks
  – \( V+H \rightarrow bb \), (where \( V=W/Z \))
  – Vector boson fusion (VBF) \( H \rightarrow bb \)
  – Boosted \( H \rightarrow bb \)
  – \( H \rightarrow bb \) combination

• Higgs coupling to charm quarks
  – \( Z+H \rightarrow bb \)
Why $ttH$?

- Explore Higgs-Fermion interactions at LHC
  - The strength of Higgs-Fermion interactions
    - Higgs-Top coupling is the largest
  - At LHC: Model dependent vs independent

Indirect detection, model dependent

direct detection in production

$ttH$: probably the only channel that can directly probe Higgs Yukawa coupling via production

**ATLAS Preliminary**

$r_s = 13$ TeV, $36.1 - 79.8$ fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$
How to study ttH?

- **Production**

- **Decays**

Top Pair Branching Fractions

- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons"
- "lepton+jets"

Hundreds of complex final states

- ~1% of total Higgs
- ~0.06% of ttbar
- ~1/10^{11} of total interaction

H decay

- bb: 58.1%
- WW: 21.5%
- ττ: 6.3%
- ZZ: 2.6%
- γγ: 0.23%

Analyzed Final states

- Jets
- τ
- Multi-leptons
- Photons
Higgs-top Yukawa coupling in run1

- Direct measurement of Higgs-Top coupling via $t\bar{t}H$ production.
- $t\bar{t}H$ signal strength ($\mu_{t\bar{t}H}$) measured in LHC Run 1
  - 4.4 sigma observed significance (ATLAS+CMS run1 combination)
  - 2.0 sigma expected significance

$$\mu = \frac{\sigma_{\text{measured}}}{\sigma_{\text{SM}}}$$

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ttH channels

- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$ (multi-leptons)
- $H \rightarrow b\bar{b}$

Higher cross section x branching ratio

Higher signal purity
• Obs. (exp.) significance at 4.1σ (2.8σ)
  – ttbar background suppressed at
    • Same sign di-lepton channel
    • 3 and 4 leptons channel
  – Major syst.
    • ttH predicted cross section
    • Jet energy scale and resolution

### ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th></th>
<th>Tot.</th>
<th>Stat.</th>
<th>(Stat., Syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\ell OS + 1τ_{had}</td>
<td>1.7</td>
<td>+2.1</td>
<td>+1.1, -1.5</td>
</tr>
<tr>
<td>1\ell + 2τ_{had}</td>
<td>-0.6</td>
<td>-1.9</td>
<td>-0.8, -1.3</td>
</tr>
<tr>
<td>4\ell</td>
<td>-0.5</td>
<td>+1.3</td>
<td>-0.8, +0.2</td>
</tr>
<tr>
<td>3\ell + 1τ_{had}</td>
<td>1.6</td>
<td>-0.9</td>
<td>+1.7, -1.3</td>
</tr>
<tr>
<td>2\ell SS + 1τ_{had}</td>
<td>3.5</td>
<td>-1.3</td>
<td>+1.5, -1.2</td>
</tr>
<tr>
<td>3\ell</td>
<td>1.8</td>
<td>-0.9</td>
<td>+0.6, -0.6</td>
</tr>
<tr>
<td>2\ell SS</td>
<td>1.5</td>
<td>-0.7</td>
<td>+0.4, -0.4</td>
</tr>
<tr>
<td>combined</td>
<td>1.6</td>
<td>0.5</td>
<td>+0.3, +0.4</td>
</tr>
</tbody>
</table>

Best-fit \( \mu_{ttH} \) for \( m_{H} = 125 \text{ GeV} \)

### Signal Fraction [%]

- H → other
- H → ττ
- H → ZZ
- H → WW

### Simulation

\[ \sqrt{s} = 13 \text{ TeV} \]
- Suffers from large QCD background from tt+bjets
- Combined fit to all 19 regions (with control region)
  - Reduce background systematics
  - Observed(expected) significance at 1.4σ (1.6σ)
Use photons to tag the Higgs Boson

Use jets (b-jets), leptons, and $E_T^{\text{miss}}$ to capture the characteristics of top quarks

Directly use properties of the objects in the event to train a multivariate discriminant
The signal strength (observed/predicted) is measured to be:

$$\mu_{t\bar{t}H} = 1.38^{+0.41}_{-0.36} = 1.38^{+0.33}_{-0.31} \text{ (stat.)}^{+0.13}_{-0.11} \text{ (exp.)}^{+0.22}_{-0.14} \text{ (theo.)}$$

Significance: 4.9σ observed (4.2σ expected.)
• Observation of ttH production!
  – \( ttH \rightarrow \gamma \gamma \) is still dominated by statistics unc.

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

- \( ttH (b\bar{b}) \)
  
  \[
  0.79 \pm 0.61^{+0.29}_{-0.28}, \pm 0.53
  \]

- \( ttH (\text{multilepton}) \)
  
  \[
  1.56 \pm 0.42^{+0.30}_{-0.29}, \pm 0.30
  \]

- \( ttH (\gamma\gamma) \)
  
  \[
  1.39 \pm 0.48^{+0.42}_{-0.38}, \pm 0.23
  \]

- \( ttH (Z\bar{Z}) \)
  
  \(<1.77 \text{ at } 68\% \text{ CL}\)

- Combined
  
  \[
  1.32 \pm 0.28^{+0.18}_{-0.26}, \pm 0.21
  \]
Higgs coupling to bottom quarks

- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)

- Higgs coupling to bottom quarks
  - $V+H \rightarrow bb$, (where $V=W/Z$)
  - Vector boson fusion (VBF) $H \rightarrow bb$
  - Boosted $H \rightarrow bb$
  - $H \rightarrow bb$ combination

- Higgs coupling to charm quarks
  - $Z+H \rightarrow bb$
Higgs decay

- **H→bb is the Dominant Decay mode of Higgs Boson (58%)**
- **Motivation:** Search H→bb decay mode in VBF final state

**ZZ, γγ:** Good mass resolution channels; mass and precise differential measurements

**WW:** High BR, poor mass resolution

**μμ:** Very small BR, but access to coupling to 2nd generation fermions

**bb, tt:** High BR, but low S/B; important to directly probe Higgs boson coupling to fermions
Road to discovery of $H \rightarrow bb$

- Started in LEP era, developed in Tevatron, found at LHC
  - $H \rightarrow bb$ observation in middle of 2018 by ATLAS and CMS
H → bb searches in different channels

- **H→bb is hadronic final state**
  - Need a clear signature for trigger in ATLAS

- Largest cross section
- Huge multi-jet (MJ) background
- Two forward jets
- Large MJ
- Leptonic signature
- Better triggering
- Better MJ suppression
- Leptonic signature
- Also top quark coupling
V+H( → bb) : event selection

0-Lepton

$E_{T}^{\text{miss}}$ trigger
Veto leptons $p_{T}>7$ GeV
$p_{T}(E_{T}^{\text{miss}}) > 150$GeV
Angular cuts to remove MJ

1-Lepton

Single-electron or $E_{T}^{\text{miss}}$ trigger
Exactly one isolated lepton
$p_{T}>25$ (27)GeV for muon (electron)
$p_{T}^{W}(l,\nu) > 150$GeV
$E_{T}^{\text{miss}}>30$ GeV in electron channel

2-Lepton

Single-lepton trigger
2 electrons or muons $p_{T}>27$ (7) GeV
$p_{T}^{Z}(l,l) [75-150$GeV$] \text{ or } >150$GeV
$81 < m_{ll} < 101$ GeV

VH → bb: strategy

- Harder $p_T^V$ spectrum for signal
  - $V=\text{W or Z}$
  - Higher S/B ratio in high $p_T$ region

- 8 signal categories:
  - Number of lepton (0,1,2-lepton)
  - $75 < p_T^V < 150 \text{ GeV (2-lepton)}, p_T^V > 150 \text{ GeV}$
  - Number of jets (2jet or 3 jets)

- Main discriminant variables
  - $m_{bb}$, $p_T^V$ and $\Delta R_{bb}$
  - $m_{bb}$ resolution extremely important!
  - Correction to $m_{bb}$
    - taking into account $p_T(\mu)$ in $b$-jets
    - for $\nu'$s and out-of-cone energy in decay
    - kinematic fit in 2-lepton channel

\[ \Delta R_{bb} \]
V+H ($\rightarrow$ bb): background

- **0-lepton**
  - Data
  - VH, H → bb ($\mu = 1.16$)
  - Diboson
  - tt
  - Single top
  - W+jets
  - Z+jets
  - Uncertainty
  - Pre-fit background
  - VH, H → bb × 5

- **1-lepton**
  - Data
  - VH, H → bb ($\mu = 1.16$)
  - Diboson
  - tt
  - Single top
  - W+jets
  - Z+jets
  - Uncertainty
  - Pre-fit background
  - VH, H → bb × 5

- **2-lepton**
  - Data
  - VH, H → bb ($\mu = 1.16$)
  - Diboson
  - Z+jets
  - tt
  - Single top
  - Uncertainty
  - Pre-fit background
  - VH, H → bb × 5

- **Z+bjets** dominates in 0, 2 lepton channels
- **Top quark and W+jets** in 1 lepton channel
- **Multi-jet background**
  - Negligible in 0/2 lepton channels after anti-QCD cuts
  - Data-driven estimate in 1 lepton channel
VH → bb: Result

Fit to BDT distributions (8 SRs)

\[ \mu = \frac{\text{observed signal yield}}{\text{signal yield from theory}} \]

\[ \mu_{bb}^{VH} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16 \text{(stat.)}^{+0.21}_{-0.19} \text{(syst.)} \]

corresponding to \(4.9\sigma\) (4.3\(\sigma\) exp.)

Fit to \(m_{bb}\) distributions (14 SRs)

\[ \mu_{bb}^{VH} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20 \text{(stat.)}^{+0.30}_{-0.26} \text{(syst.)} \]

corresponding to \(3.6\sigma\) (3.5\(\sigma\) exp.)
Higgs coupling to bottom quarks

- Higgs coupling to top quarks
  - Associated production with a top quark pair (ttH)
- Higgs coupling to bottom quarks
  - $V+H \rightarrow bb$, (where $V=W/Z$)
  - Vector boson fusion (VBF) $H \rightarrow bb$
  - Boosted $H \rightarrow bb$
  - $H \rightarrow bb$ combination
- Higgs coupling to charm quarks
  - $Z+H \rightarrow bb$
VBF H $\rightarrow$ bb analysis

- Search for H-$\rightarrow$bb in VBF events with/without photons
- Advantages of requiring a photon
  - extra handle for trigger
  - suppresses QCD background

VBF H $\rightarrow$ bb

VBF H $\rightarrow$ bb + $\gamma$
VBF $H \rightarrow bb$ result

- 1.9σ (0.7σ) Observed (Expected) significance
  - By combing all VBF $H \rightarrow bb$ channels

VBF $H \rightarrow bb$

Background uncertainty is the major systematics uncertainty

VBF $H \rightarrow bb + \gamma$

Statistics uncertainty dominated

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Higgs coupling to bottom quarks

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- Higgs coupling to charm quarks
  - $Z+H \rightarrow bb$
- Looking for a high $p_T$ large radius jet with two b-tags
  - Leading jet ($R=1.0$) $p_T>480\text{GeV}$, sub-leading jet $p_T>250\text{GeV}$
  - Two b tagged track jets in leading jet
  - $\mu_H=5.8\pm3.1(\text{stat.})\pm1.9(\text{syst.})\pm1.7(\text{th.})$
  - 1.6 $\sigma$ observed significance

signal = ggF + VBF + VH
Higgs coupling to bottom quarks

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- Higgs coupling to charm quarks
  - $Z+H \rightarrow bb$
Observation of $H \rightarrow bb$

- **VH $\rightarrow bb$ in Run 2:**
  - Observed (expected) of $4.9\sigma$ ($4.3\sigma$)
- **Adding VH $\rightarrow bb$ in Run1**
  - Observed (expected) of $4.9\sigma$ ($5.1\sigma$)
- **Adding VBF and ttH**
  - Observed (expected) of $5.4\sigma$ ($5.5\sigma$)
  - Observation of $H \rightarrow bb$ decay

- **Adding $H \rightarrow ZZ$ and $H \rightarrow \gamma \gamma$:**
  - Observed (expected) of $5.4\sigma$ ($5.5\sigma$)
  - Observation of VH production
**VH → bb: Differential cross section**

- Differential cross section measurements for W/Z boson $p_T$
  - In the ‘simplified template cross-section’ framework.
  - Constraint to new physics in Higgs Effective Lagrangian (HEL)

![ATLAS VH, H→bb, V→leptons cross-sections: Observed, Total unc., Statistical unc., SM, Theoretical unc.](image)

**ATLAS Simulation**

- $\bar{c}_{HW} = 0.004$
- $\bar{c}_{HB} = 0.024$
- $\bar{c}_W - \bar{c}_B = 0.008$
- $\bar{c}_d = 0.5$

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Higgs coupling to charm quarks

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  - $H \rightarrow bb$ combination

- Higgs coupling to charm quarks
  - $Z+H \rightarrow bb$
Search for $H \rightarrow cc$

- Charm jet tagging performance is the key.

**Cross check with diboson**
- $ZZ \rightarrow llcc$ and $WZ \rightarrow (cs/cd)ll$
- Run2 36.1 fb$^{-1}$ result:
  - Obs.(exp.) significance: 1.4 (2.2) $\sigma$

**2 Leptons: $ZH \rightarrow llcc$**
- $p_T^Z > 75$ GeV
- $81 < m_\ell < 101$ GeV

<table>
<thead>
<tr>
<th>0 Lepton: $ZH \rightarrow \ell\nu\ell\nu$</th>
<th>1 Lepton: $WH \rightarrow \ell\nu\ell\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>as $VH, H \rightarrow bb$</td>
<td>as $VH, H \rightarrow bb$</td>
</tr>
</tbody>
</table>

- $\geq 2$ jets, with 1 or 2 c-tags
- $p_T(c1) > 45$ GeV

**ATLAS Simulation**
- $\sqrt{s} = 13$ TeV, $tt$

**ATLAS Simulation**
- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - 2 c-tags, $p_T^Z \geq 150$ GeV

**Flavour composition**
- $\ell\ell$, $cl$, $cc$, $bl$, $bc$, $bb$

$75$ GeV $< p_T^Z < 150$ GeV $\rightarrow \Delta R < 2.2$

$150$ GeV $< p_T^Z < 200$ GeV $\rightarrow \Delta R < 1.5$

$p_T^Z > 200$ GeV $\rightarrow \Delta R < 1.3$
Search for $H \to cc$: result

- $Z(\ell\ell)H(\rightarrow cc)$ has been studied in run2 with $36.1 \text{ fb}^{-1}$.
  - $H \rightarrow \J/\psi\gamma$ search on ATLAS gives similar precision.
- Also extrapolated to $3000 \text{ fb}^{-1}$.

$\mu_{ZH(cc)} < 110 \quad 36.1 \text{ fb}^{-1}$

$\mu_{ZH(cc)} < 6.3^{+2.5}_{-1.8} \quad 3000 \text{ fb}^{-1}$

ATLAS Simulation Preliminary
$\sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1}$
2 c-tags, $p_T^Z \geq 150 \text{ GeV}$
Summary

- **With the large LHC Run 2 dataset,**
  - the coupling of the Higgs boson to quarks can be determined with unprecedented precision
  - **Confirmation of coupling to 3rd generation fermions**
  - Recent observation bottom and top quark Higgs coupling were presented
  - Observation of VH and ttH production shown

- **All measurements of the Higgs boson are compatible with the Standard Model**
**VBF H \rightarrow bb: Event Selection**

<table>
<thead>
<tr>
<th></th>
<th>Two central</th>
<th>Four central</th>
<th>Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2 \text{ b-jet} )</td>
<td>(p_T &gt; 95 \text{GeV} ) (p_T &gt; 70 \text{GeV} )</td>
<td>(p_T &gt; 55 \text{GeV} )</td>
<td>(p_T &gt; 40 \text{GeV} )</td>
</tr>
<tr>
<td>(2 \text{ VBF jets} )</td>
<td>(p_T &gt; 60 \text{GeV}, 3.2 &lt;</td>
<td>\eta</td>
<td>&lt; 4.4 ) (p_T &gt; 20 \text{GeV},</td>
</tr>
<tr>
<td><strong>Photon</strong></td>
<td></td>
<td></td>
<td>(E_T &gt; 30 \text{GeV} )</td>
</tr>
<tr>
<td><strong>Event topology</strong></td>
<td>(p_T(\text{bb}) &gt; 160 \text{GeV} )</td>
<td>(p_T(\text{bb}) &gt; 150 \text{GeV} )</td>
<td>(p_T(\text{bb}) &gt; 80 \text{GeV} ) M(jj) &gt; 800 \text{GeV}</td>
</tr>
</tbody>
</table>

Inclusive analysis veto data events in photon channel orthogonality between different channels
- Select events based on $m_{\gamma\gamma} + b$-jets
  - Significance: $4.1\sigma$ ($3.7\sigma$ exp.)
Boosted Decision Tree (BDT) Analysis

- 11 variables used in BDT analysis

\[ \text{centrality}(\gamma) = \left| \frac{y_\gamma - \frac{y_{j1} + y_{j2}}{2}}{y_{j1} - y_{j2}} \right| \]

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV} \)
VBF H\( \rightarrow \text{bb, photon channel} \)

<table>
<thead>
<tr>
<th>VBF H(bb) Inclusive</th>
<th>VBF H(bb)+Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/q separation</td>
<td>Ntrk(j1), Ntrk(j2)</td>
</tr>
<tr>
<td></td>
<td>( \min \Delta R(J1), \min \Delta R(J2) )</td>
</tr>
<tr>
<td>VBF jets</td>
<td>( p_{(JJ)}, M(JJ), \Delta M(JJ) )</td>
</tr>
<tr>
<td></td>
<td>( \max(\eta(J1), \eta(J2)) )</td>
</tr>
<tr>
<td>Color connection</td>
<td>( p_{\text{balance}} )</td>
</tr>
<tr>
<td></td>
<td>( \eta^\gamma ) (Higgs centrality)</td>
</tr>
<tr>
<td>Angular</td>
<td>( \cos \theta(bb,jj) )</td>
</tr>
</tbody>
</table>
ATLAS

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

\( m_H = 125 \text{ GeV} \)

**tot (stat syst)**

Dilepton (two-\( \mu \) combined fit)

-0.24

\(+1.02 \) \(+0.54 \) \(+0.87 \)

\(-1.05 \) \(-0.52 \) \(-0.91 \)

Single Lepton (two-\( \mu \) combined fit)

0.95

\(+0.65 \) \(+0.31 \) \(+0.57 \)

\(-0.62 \) \(-0.31 \) \(-0.54 \)

Combined

0.84

\(+0.64 \) \(+0.29 \) \(+0.57 \)

\(-0.61 \) \(-0.29 \) \(-0.54 \)

Best fit \( \mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{\text{SM}} \)
ttH multilepton

Number of $\tau_{\text{had}}$

2

1

0

Number of light leptons

1

2

3

4

$1\ell+2\tau_{\text{had}}$

$2\ell_{\text{SS}}+1\tau_{\text{had}}$

$2\ell_{\text{OS}}+1\tau_{\text{had}}$

$3\ell+1\tau_{\text{had}}$

$2\ell_{\text{SS}}$

$3\ell$

$4\ell$
ATLAS Detector upgrade: Run 1 to Run 2

- Adding a new layer of pixel detector
- IBL = New Insertable pixel B-Layer at R=33 mm
B tagging performance Improvement

- Light jet rejection power with vertexing algorithm increased
  - Benefitting from IBL detector
**VH → bb: Multivariate Analysis (MVA)**

- **MVA setup**
  - Use simple and robust **Boosted Decision Tree (BDT)**
  - Input variables and training parameters tuned to yield best sensitivity

- **Inputs Variables**
  - Kinematic variables, some specific to 3-jet regions
  - $m_{bb}$, $\Delta R_{bb}$, $p_T^V$ most important ones

### Table: Variables and Sensitivity

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^V$</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{miss}$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$p_T^T$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R(b_1, b_2)$</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[\Delta \eta(b_1, b_2)]$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi(V, bb)$</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[\Delta \eta(V, bb)]$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$m_{eff}$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$\min[\Delta \phi(\ell, b)]$</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>$m_W$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_T$</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$m_{\ell}$</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$E_{miss}/\sqrt{S_T}$</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$m_{op}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[\Delta Y(V, bb)]$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Only in 3-jet events:

- $p_T^{jet_3}$
- $m_{bbj}$
7 signal regions (categories) are used.

- Di-photon mass resolution is slightly different in different categories.
ttH combination

Observation of ttH production!

ATLAS (up to 80 fb-1)
Run-2: 5.8σ (4.9σ exp.)
Run-1+Run-2: 6.3σ (5.1σ exp.)

Compute signal strength $\sigma_{ttH}/\sigma_{ttH}$ from profile likelihood fit over all channels. Correlate systematic uncertainties were appropriate.

Sensitivity limited by theory uncertainties on signal and background modelling.

$ttH \rightarrow \gamma \gamma$ is still dominated by statistics unc.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \sigma_{ttH}/\sigma_{ttH}$ [%]</th>
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<tbody>
<tr>
<td>Theory uncertainties (modelling)</td>
<td>11.9</td>
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<tr>
<td>$t\bar{t}$ + heavy flavour</td>
<td>9.9</td>
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<tr>
<td>$t\bar{t}H$</td>
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<tr>
<td>Non-$t\bar{t}H$ Higgs boson production</td>
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<tr>
<td>Other background processes</td>
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<tr>
<td>Experimental uncertainties</td>
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<tr>
<td>Fake leptons</td>
<td>5.2</td>
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<tr>
<td>Jets, $E_T^{miss}$</td>
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<tr>
<td>Electrons, photons</td>
<td>3.2</td>
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<tr>
<td>Luminosity</td>
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<td>$\tau$-leptons</td>
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<tr>
<td>Flavour tagging</td>
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<tr>
<td>MC statistical uncertainties</td>
<td>4.4</td>
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