ATLAS Results on tt+Higgs

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on behalf of the ATLAS collaboration
ICNFP 2019, Aug 24th, Crete Greece
Introduction – Higgs boson production at the LHC

Gluon Fusion

\[ \sigma_{H,ggF} \approx 49 \text{ pb} \]

Vector Boson Fusion

\[ \sigma_{VBF} \approx 3.8 \text{ pb} \]

Higgs-Strahlung

\[ \sigma_{W/Z+H} \approx 1.4/0.9 \text{ pb} \]

\[ \sigma_{ttH} \approx 0.507 \text{ pb} \]

Cross sections for \( m_H = 125 \text{ GeV}, \sqrt{s} = 13 \text{ TeV} \)

- \( ttH \) has small cross section (1/100 ggF)
- Large increase 8TeV \( \rightarrow \) 13 TeV (x3.9)
- Complex final states
- Large Standard Model (SM) backgrounds

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{pp \rightarrow H+X} ) (pb)</td>
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</tr>
<tr>
<td>( \sigma_{ggF} )</td>
<td>( \sigma_{VBF} )</td>
</tr>
<tr>
<td>( \sigma_{W/Z} )</td>
<td>( \sigma_{ttH} )</td>
</tr>
<tr>
<td>( \sigma_{W/Z+H} )</td>
<td>( \sigma_{H,ggF} )</td>
</tr>
</tbody>
</table>

Run-1

Run-2

- Small increase 8 TeV \( \rightarrow \) 13 TeV (x1.1)
- Simple final states
Introduction – Higgs Boson Interactions

**Gauge couplings:** Key in Higgs discovery (ZZ, WW, $\gamma\gamma$)

**Yukawa couplings:** Higgs boson properties

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**Yukawas at LHC**

<table>
<thead>
<tr>
<th></th>
<th>tau</th>
<th>b</th>
<th>top</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Exp. Sig.</td>
<td>5.4 $\sigma$</td>
<td>5.5 $\sigma$</td>
<td>5.1 $\sigma$</td>
</tr>
<tr>
<td>Obs. Sig.</td>
<td>6.4 $\sigma$</td>
<td>5.4 $\sigma$</td>
<td>6.3 $\sigma$</td>
</tr>
<tr>
<td>mu</td>
<td>1.09 $\pm$ 0.35</td>
<td>1.01 $\pm$ 0.20</td>
<td>1.34 $\pm$ 0.21 $^*$</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Exp. Sig.</td>
<td>5.9 $\sigma$</td>
<td>5.6 $\sigma$</td>
<td>4.2 $\sigma$</td>
</tr>
<tr>
<td>Obs. Sig.</td>
<td>5.9 $\sigma$</td>
<td>5.5 $\sigma$</td>
<td>5.2 $\sigma$</td>
</tr>
<tr>
<td>mu</td>
<td>1.09 $\pm$ 0.27 $^*$</td>
<td>1.04 $\pm$ 0.20</td>
<td>1.26 $\pm$ 0.26 $^{**}$</td>
</tr>
</tbody>
</table>

* 13 TeV only derived from cross section measurements

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Key Run 2 milestones **accomplished** - **Discovery of 3$^{\text{rd}}$ generation Higgs boson Yukawas!**
Introduction – Motivation for ttH Measurement

- All LHC Higgs property measurements consistent with SM so far...
- Goal: Probing the **top-Higgs Yukawa** $y_t$
  - Largest in the SM: $y_t = \sqrt{2} \frac{m_t}{v} \approx 1$ (intriguing?)
  - Sensitive to potential New Physics
- **Indirect measurement of** $y_t$ **from** ggF **production and** $H \rightarrow \gamma\gamma$ **(but relies on assumptions in loop)**

- ttH production provides **direct probe of** $y_t$
  
  (tH also contributes complementary information)

**ATLAS Preliminary**

$m_F$ or $\sqrt{\kappa_{FV}}$

$\sqrt{s} = 13$ TeV, 24.5 - 139 fb$^{-1}$

$m_H = 125.09$ GeV

$\kappa_F$ or $\sqrt{\kappa_{FV}}$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$12$

$1.2$

$1$

$0.8$

Particle mass [GeV]

Direct and indirect probes of $y_t$ allow to simultaneously constrain top Yukawa coupling and possible New Physics effects...
Introduction – Standard Model Cross Sections Measurements

Standard Model Production Cross Section Measurements

\[ \sigma \text{ [pb]} \]

ATLAS Preliminary

Run 1,2 \( \sqrt{s} = 5,7,8,13 \) TeV

- Few hundred billion pp collisions to produce a ttH event
- Higgs /100
- ttH
ttH Signatures – The Decay of the ttH System

- Top quark ($t \rightarrow Wb$) and Higgs boson decays ($H \rightarrow X$) result in rich spectrum of signatures
- Broad range of analyses explored to capture these complex final states with many objects: Leptons [$e, \mu, \tau_{\text{had}}$, jets, $b$-jets, photons, $E_{T\text{miss}}$]
  - Need good understanding of reconstructed objects
  - Good efficiency (excellent detector performance, hard work of performance groups!)
- ATLAS explored all of these multiple final states given small ttH production rate

**Combination of all these analyses for best sensitivity and cross-check**
## ATLAS ttH Analyses

<table>
<thead>
<tr>
<th>Higgs Decay</th>
<th>ttH - Multilepton (H→WW*, ZZ* and H→ττ)</th>
<th>ttH (H→bb)</th>
<th>Combination</th>
<th>ttH (H→γγ) - Diphoton</th>
<th>ttH (H→ZZ*→4l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36 fb⁻¹</td>
<td>36 fb⁻¹</td>
<td>36 - 80 fb⁻¹</td>
<td>140 fb⁻¹</td>
<td>140 fb⁻¹</td>
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**Phys. Rev. D 97, 072003**

**Phys. Rev. D 97, 072016**


**ATLAS-CNF-2019-004**

**ATLAS-CNF-2019-025**

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ATLAS casts a wide net, with analyses designed to target the various Higgs boson decays.

- **bb (58.1%)**
- **WW (21.5%)**
- **ττ (6.3%)**
- **ZZ (2.6%)**
- **γγ (0.2%)**
- **other (11.2%)**

smaller BR, higher purity (generally)
**Analysis Strategy — Cascade of MVAs**

**Categorization:**
- 10 CRs normalizing backgrounds
- 9 SRs to enhance purity, #jets, b-tagging (4 working points)

**Reconstruction:**
- Reco-BDT
- Matrix element method
- Likelihood discriminant

**Classification**
- BDT ttH vs tt-background
- Include event kinematics, b-tag info, reco MVAs

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**ttH \( (H\to bb) \)** Analysis

- ttH(bb) most abundant (BR=58%), but large irreducible background with big theoretical uncertainty (from tt+bb)
- Higgs boson reconstruction possible, but challenging due to \( b_{\text{jet}}, b_{\text{parton}} \) combinatorics (\( b_{\text{jets}} \) from Higgs and top quark decay)
- **Challenge:** Modeling of tt+HeavyFlavor background
- Define various signal (SRs) and data control regions (CRs)
ttH (H→bb) Analysis

Signal extraction:
Binned profile likelihood fit to all signal and control regions. Normalisation of \(tt \geq 1b\) and \(tt \geq 1c\) left free-floating in the fit.

Signal strength: \(\mu = \sigma/\sigma_{SM}\)

ATLAS
\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
\(m_H = 125\) GeV

- 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)

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

Dominant systematics (\(\Delta\mu\))
- Modelling of \(\bar{t}t + \geq 1b\) (±0.46)
- Monte Carlo statistics (±0.30)
- Jet flavour tagging (±0.16)
- Jet energy scale & resolution (±0.16)

Analysis is systematically limited
Requires improvements from both theory and experimental communities!
**ttH – Multilepton Analysis**

- **Targeting:** $ttH \rightarrow WW^* \rightarrow (\ell\nu\ell\nu, \ell\nu qq)$, $H \rightarrow \tau\tau$ and $H \rightarrow ZZ^* \rightarrow (\ell\nu\ell\nu, \ell\nu qq)$ decays
- With leptonic $tt$ decays, this leads to distinct signatures
- 7 orthogonal channels categorised by multiplicity of $e/\mu$ and hadronic tau ($\tau_{\text{had}}$) candidates, $b$-jet multiplicity
- Develop CRs to normalize backgrounds
- Use of BDTs in SRs to further improve purity
- Analysis does not rely on Higgs mass reconstruction

**Event categorization based on $\#\text{leptons}$ and $\#\tau_{\text{had}}$**

- $1\ell+2\tau_{\text{had}}$
- $2\ell SS+1\tau_{\text{had}}$
- $2\ell OS+1\tau_{\text{had}}$
- $3\ell+1\tau_{\text{had}}$
- $4\ell$
- $2\ell SS$
- $3\ell$
- $4\ell$
Main backgrounds:
- **Reducible**: Non-prompt e, \(\mu\) and hadronic \(\tau\) and prompt light leptons with misidentified charge
- Develop object level discrimination to reduce these backgrounds
  - Isolation BDT to reduce non-prompt background
  - Charge mis-ID BDT
- **Irreducible**: ttV and VV – estimated from MC and validated in data.
ttH – Multilepton Analysis

Signal extraction:
Simultaneous likelihood fit to all categories including control regions of main backgrounds

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

**Dominant systematics ($\Delta \mu$)**
- Modelling of $ttH$ (+0.20, -0.10)
- Jet energy scale, b-tagging (±0.16)
- Non-prompt $e/\mu$ (±0.14)
- $ttV$ backgrounds (±0.10)

More data will improve the precision on channels that are still stats. limited and help constraining $ttZ$ & $ttW$ background.

Significance: 4.1$\sigma$ (expected 2.8$\sigma$)
ttH – Diphophoton Analysis

Very similar strategy for 79.8 fb\(^{-1}\) and full Run 2 (139 fb\(^{-1}\)) analysis

- Split sample by leptonic (≥1ℓ) and hadronic x(0ℓ) ttbar decays (incl. b-tag)
- Boosted Decision Trees (BDT) to enhance purity in sample
- BDT input based on lepton, jet, photon 4-vectors (trained mass-independent), \(E_T^{\text{miss}}\) and b-tag

- Very small rate !!
- Remember \(\sigma_{\text{ttH}} = 1\%\) \(\sigma_{\text{ggF}}\) and \(\text{BR}(H \rightarrow \gamma\gamma) = 0.2\%\)
- Select two isolated photons with 105 GeV < \(M_{\gamma\gamma}\) < 160 GeV
- Additional selection using MVAs for hadronic and leptonic tt decay to improve purity (enabling this analysis)

![Graph showing signal and background distributions](image.png)

\(H \rightarrow \gamma\gamma, m_H = 125\) GeV

**ATLAS Simulation Preliminary**

\(\sqrt{s} = 13\) TeV, 139 fb\(^{-1}\)

- Had 1
  - MC
  - Signal Model

- Lep 3
  - MC
  - Signal Model
ttH – Diphotos Analysis

- Very small rate !
- Remember $\sigma_{ttH} = 1\%$ $\sigma_{ggF}$ and $\text{BR}(H \rightarrow \gamma\gamma) = 0.2\%$
- Select two isolated photons with $105 \text{ GeV} < M_{\gamma\gamma} < 160 \text{ GeV}$
- Additional selection using MVAs for hadronic and leptonic $tt$ decay to improve purity (enabling this analysis)

**Categorize events by BDT score (signal purity)**

- Select 4 hadronic (HAD1-HAD4) and 3 leptonic (LEP1-LEP3) categories
- BDT sub-samples optimized for best sensitivity
- Low BDT score events are rejected
ttH – Diboson Analysis

- Very small rate!!
- Remember $\sigma_{ttH} = 1\%$ $\sigma_{ggF}$ and $\text{BR}(H \to \gamma\gamma) = 0.2\%$
- Select two isolated photons with $105 \text{ GeV} < M_{\gamma\gamma} < 160 \text{ GeV}$
- Additional selection using MVAs for hadronic and leptonic tt decay to improve purity (enabling this analysis)

**Dominant uncertainties**
- Parton shower & underlying event ($\pm 0.06$)
- Photon energy resolution, scale ($\pm 0.06$)
**ttH – Diboson Analysis (80 fb\(^{-1}\) result)**

**Signal extraction**

Performed by simultaneous **unbinned** maximum likelihood fit of \(m_{\gamma\gamma}\) spectra (105-160 GeV) in all 7 categories

- H mass constrained
- **Signal and background** modeled with analytic functions

---

**Observed significance:** 4.1\(\sigma\)  
(Expected: 3.7\(\sigma\))

\[
\sigma_{ttH} = 710 \pm^{+210}_{-190} \text{ (stat.)} \pm^{+120}_{-90} \text{ (syst.)} \text{ fb}
\]

\[
\frac{\sigma_{ttH}}{\sigma_{ttH}^{SM}} = 1.39 \pm^{+0.42}_{-0.38} \text{ (Stat.)} \pm^{+0.23}_{-0.17} \text{ (Syst.)}
\]
ttH – Diphoton Analysis (140 fb⁻¹ result)

**Signal extraction**
Performed by simultaneous **unbinned maximum likelihood fit** of $m_{\gamma\gamma}$ spectra (105-160 GeV) in all **7 categories**
- H mass constrained
- **Signal and background** modeled with analytic functions
- Analyze full Run-2 dataset with updated photon-ID, energy and jet calibrations

**2019**: First observation of single ttH channel with 4.9σ significance (4.2σ exp)

\[
\sigma_{ttH} \times B_{\gamma\gamma} = 1.59^{+0.38}_{-0.36} \text{(stat.)}^{+0.15}_{-0.12} \text{(exp.)}^{+0.15}_{-0.11} \text{(theo.)} \text{ fb}
\]

\[
\frac{\sigma_{ttH}}{\sigma_{SM}} = 1.38 \pm^{0.33}_{0.31} \text{ (Stat.)} \pm^{0.13}_{0.11} \text{ (exp.)} \pm^{0.22}_{0.14} \text{ (theo.)}
\]

**Note:**
- Events weighted by purity
- Non-ttH Higgs boson processes from MC samples normalized to their expected SM cross sections times the expected SM branching ratio to di-photons with a Higgs boson mass of 125 GeV

**Analysis still stats limited!**
Combination of ttH Analyses (36…80 fb⁻¹)

2018: Combining 4 analyses: 6.3σ Observation (5.1σ Exp)

Significance

<table>
<thead>
<tr>
<th></th>
<th>Obs</th>
<th>(Exp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH (b\bar{b})</td>
<td>1.4σ</td>
<td>(1.6σ)</td>
</tr>
<tr>
<td>ttH (multilepton)</td>
<td>4.1σ</td>
<td>(2.8σ)</td>
</tr>
<tr>
<td>ttH (γγ)</td>
<td>4.1σ</td>
<td>(3.7σ)</td>
</tr>
<tr>
<td>ttH (ZZ)</td>
<td>0σ</td>
<td>(1.2σ)</td>
</tr>
<tr>
<td>Combined</td>
<td>5.8σ</td>
<td>(4.9σ)</td>
</tr>
<tr>
<td></td>
<td>6.3σ (5.1σ)</td>
<td></td>
</tr>
</tbody>
</table>

13 TeV only
7,8 and 13 TeV

Some details:
- Theory uncertainties correlated, experimental uncertainties mostly uncorrelated
- Other Higgs boson production modes constrained to Standard Model prediction
- Assume Standard Model branching ratios

Major milestone in Run-2 accomplished

Combination of ttH Analyses – First Observation!

by ATLAS

Visualize of ttH signal signal across all channels binned according to purity

σ_{ttH}^{SM} = 507 fb

Combined (13 TeV) 36.1–79.8 670 ± 90 (stat.) ^{+110}_{-100} (syst.)
Total $ttH$ cross-section

Data agrees with predicted strong ($\times 3.9$) rise in cross-section vs $\sqrt{s}$

Cross-section extracted assuming SM Higgs branching fractions

670 ± 90 (stat) ±105 (syst) fb
(13%) (16%)

220 ± 100 (stat) ± 70 (syst) fb
(45%) (32%)
ttH (H→ZZ*→4l) Analysis

- New ATLAS H→ZZ*→4l analysis targeting all production modes
- Select two same-flavor lepton pairs in Higgs mass window
- Various event categorization depending on production mode
- For ttH, extremely small rate \[ \text{BR}(H\rightarrow ZZ^* \rightarrow 4l) = 0.0124\% \]
- 79.8 fb⁻¹: similar strategy but only focusing on ttH
  → Expected significance 1.2 σ, no events were observed

Two categories for ttH analysis:
- **Lep**: at least one leptonically decaying W (from top decay)
- **Had**: Fully hadronic tt decay
- Further Neural Net (NN) selection

**ATLAS Simulation Preliminary**

H → ZZ* → 4l
13 TeV, 139 fb⁻¹

0j-\(p_T\)-Low
0j-\(p_T\)-Med
1j-\(p_T\)-Low
1j-\(p_T\)-Med
1j-\(p_T\)-High
1j-\(p_T\)-BSM-Like
2j-BSM-Like
VH-Lep-enriched
0j-\(p_T\)-High

**ATLAS-CONF-2019-025**
ttH ($H \rightarrow ZZ^* \rightarrow 4l$) Analysis

**Signal extraction**

**Maximum likelihood fit** to NN output
- Most important ttV backgrounds constrained from control region (selected based on (b)-jets, MET, $M_{4l}$)

<table>
<thead>
<tr>
<th>Reconstructed event category</th>
<th>Total expected events</th>
<th>Observed events</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH-Had-enriched</td>
<td>1.32 ± 0.17</td>
<td>1</td>
</tr>
<tr>
<td>ttH-Lep-enriched</td>
<td>0.42 ± 0.04</td>
<td>1</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

$H \rightarrow ZZ^* \rightarrow 4l$
13 TeV, 139 fb$^{-1}$
Stage 0 - $|y_{H}| < 2.5$

\[ \sigma_{ttH} \times B_{ZZ^* \rightarrow 4l} \ (SM) = 15.4 \, ^{+1.0}_{-1.4} \, \text{fb} \]

\[ \sigma_{ttH} \times B_{ZZ^* \rightarrow 4l} = 19 \, ^{+22}_{-13} \,(\text{stat.}) \, \pm 2(\text{exp.}) \, \pm 2(\text{theo.}) \, \text{fb} \]
Measurement of top-Higgs Yukawa Coupling (up to 80 fb\(^{-1}\))

Assuming only Standard Model particles

\[
\kappa_{\text{top}} = \frac{y_t}{y_t^{\text{SM}}} = 1.02^{+0.11}_{-0.10}
\]

Allowing New Particles in the Loops

\[
\kappa^{2}_{\text{gluon}}
\]

\[
\kappa_{\text{top}} = \frac{y_t}{y_t^{\text{SM}}} = 1.14^{+0.19}_{-0.18}
\]

- Analysis using up to 80 fb\(^{-1}\)
- Included single parameter B\(_{\text{BSM}}\) in model
- Constrains BSM contribution in the loop (ATLAS evaluates 2HDM and MSSM as benchmark models)
- Consistent with SM Higgs boson coupling

ATLAS-CONF-2019-005
Conclusions

- ATLAS has established observation of $ttH$ production $6.3\sigma$ ($5.1\sigma$ expected) by combining the $H\rightarrow bb$, multilepton and diphoton channels
- Recent ATLAS $ttH$ observation ($4.9\sigma$) using $H\rightarrow \gamma\gamma$ channel alone
- Top-Higgs Yukawa coupling consistent with SM (within uncertainties)
- Future measurements of $tH$ production will add complementary information
- Discovery of all 3rd generation Higgs boson Yukawas (together with $H\rightarrow bb$, $\tau\tau$)

Looking into the future
- Upgrades for the HL-LHC are underway
- HL-LHC Higgs physics shows impressive goals
  - $ttH$ ($H\rightarrow bb$) to 7-11% (requires $\times2$-$3$ improvement in $tt+HF$ uncertainty, ongoing work in HXSWG)
  - $ttH$ ($H\rightarrow$multilepton) measured to 7-11% ($\Delta\mu$)
  - No projection for $ttH$ ($H\rightarrow \gamma\gamma$) yet
- New ideas will continue to push the frontiers of particle physics at the LHC.
Thank you

More Information:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults