Search for Higgs Bosons produced in association with top quarks with ATLAS detector

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on behalf of the ATLAS collaboration

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2 - 9 July, Valencia, Spain
After the Higgs discovery main focus is on the measurement of its properties:
- couplings to fermions and gauge boson
- Top quark is the most strongly-coupled SM particle ($Y_t \sim 1$)

Indirect constraints on the top-Higgs Yukawa coupling $Y_t$
- loop diagrams with top quarks contribute to ggH production and $H \rightarrow \gamma\gamma$ decays
- assumes no new particles

Direct measurement of $Y_t$ in $ttH$ production
- allows probing new physics in ggH and $\gamma\gamma H$ effective vertices

$tH$ production is sensitive to the sign of Higgs Yukawa coupling $Y_t$
Production

- \( \sigma(t\bar{t}H) \) is known at NLO QCD
- suppressed compared to other modes
- \( \approx 2600 \) events in 20.3 fb\(^{-1}\) at 8 TeV

Main background

- \( t\bar{t} + X \)

\[ \begin{array}{|c|c|c|c|}
\hline
\sqrt{s} \text{ (TeV)} & 7 & 8 & 14 \\
\hline
\hline
\begin{array}{c}
t\bar{t}H \\
(m_H = 125 \text{ GeV}) \text{ (fb)}
\end{array} & 86 & 130 & 611 \\
\hline
\begin{array}{c}
t\bar{t} \\
\text{(pb)}
\end{array} & 177 & 253 & 950 \\
\hline
\end{array} \]

- \( t\bar{t}H \) dominant mode but large background
- \( H \rightarrow \gamma\gamma \) tiny but has clean resonant signature
- multi-lepton final states
$ttH(\gamma\gamma)$
Analysis strategy

- Event selection (8 TeV)
  - diphoton trigger
  - hadronic $\bar{t}t$ category: "or" of three selections ($5 \text{ or } \geq 6$ jets, $1 \text{ or } \geq 2$ b-jets with variable jet $p_T$ thresholds and b-tagging WP)
  - leptonic $\bar{t}t$ category: $\geq 1$ lepton, $\geq 1$ b-jets, minimum $E_T^{\text{miss}}$
  - 2 isolated high $p_T$ photons
  - combined selection efficiency - 15.3%

- Search for a resonance in $m(\gamma\gamma)$
  - describe $m(\gamma\gamma)$ for background with the exponential function
  - same shape for 7 and 8 TeV and both categories

- Signal is extracted via unbinned likelihood fit to both categories and 7 and 8 TeV

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sqrt{s}$</th>
<th>$N_S$</th>
<th>$N_B$</th>
<th>$ttH$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic</td>
<td>8</td>
<td>0.60</td>
<td>$1.0^{+0.6}_{-0.4}$</td>
<td>81.0</td>
</tr>
<tr>
<td>Hadronic</td>
<td>8</td>
<td>0.51</td>
<td>$2.8^{+0.8}_{-0.7}$</td>
<td>83.7</td>
</tr>
<tr>
<td>Leptonic</td>
<td>7</td>
<td>0.10</td>
<td>$0.6^{+0.5}_{-0.4}$</td>
<td>73.0</td>
</tr>
<tr>
<td>Hadronic</td>
<td>7</td>
<td>0.07</td>
<td>$0.6^{+0.4}_{-0.4}$</td>
<td>81.2</td>
</tr>
</tbody>
</table>

- high purity $\bar{t}tH$ selection
- statistically limited
  - small impact of systematics
Combination of leptonic and hadronic channels

95% CL observed (expected) limit:

\[ 6.5 \times \text{SM} \,(4.9 \times \text{SM}) \]

for \( m_H = 125.4 \text{ GeV} \)

ATLAS-CONF-2014-043
- **tH production is suppressed with respect to ttH**
  - destructive interference between diagrams with Higgs emitted from W and Higgs emitted off top
- **In BSM theories Y_t sign can be flipped**
  - increases tH cross section and \( H \rightarrow \gamma\gamma \) branching ratio
- **Set limit on inclusive Higgs production cross section as a function of strength parameter**
  \( \kappa_t = Y_t / Y_t^{SM} \)
  - \( \kappa_t \) changes cross sections of all Higgs production modes and \( B(H \rightarrow \gamma\gamma) \)
  - set other couplings to SM value
  - null hypothesis: B+ttH(SM)

95% CL lower and upper observed (expected) limits on \( \kappa_t: -1.3 \) and +8.1 (−1.2 and +7.9)
$t\bar{t}H(\gamma\gamma)$ candidate event
FCNC in top decay

- Flavor changing neutral current
  - forbidden at tree level in SM
  - suppressed at high orders in SM

- BSM model allow FCNC
  - $t \rightarrow cH$: largest branching in 2HDM type III

$$\bar{t}t \rightarrow (Wb) \ (cH(\gamma\gamma))$$

- Event selection
  - diphoton trigger
  - 2 isolated high $p_T$ photons
  - hadronic $W$ category: 4 jets, $\geq 1$ b-jets,
  - leptonic $W$ category: $\geq 1$ lepton, 2 jets, $\geq 1$ b-jets,
    $m_T^{W} > 30$ GeV
  - Mass cuts
    - $156 < M(\gamma\gamma) < 191$ GeV
    - hadronic: $130 < M(jj) < 210$ GeV
    - leptonic: $135 < M(l\nu j) < 205$ GeV

- Search for a $m(\gamma\gamma)$ resonance

95% CL observed (expected) limit
- on $\text{Br}(t \rightarrow Hc)$: 0.83% (0.53%)
- on $\lambda_{tcH}$: 0.17 (0.14)

ATL-CONF-2013-081
$t\bar{t}H(b\bar{b})$
Analysis strategy

- **Event selection**
  - Single lepton channel: 1 lepton (e or μ), from 4 to ≥ 6 jets with 2 to ≥ 4 b-jets
  - Dilepton channel: 2 opposite-sign leptons (ee, μμ, eμ), from 2 to ≥ 4 jets with 2 to ≥ 4 b-jets

- **Categorize events by jet and b-jet multiplicity**
  - take advantage of low S/B regions to constrain systematic uncertainties
  - maximize sensitivity by separating regions with different S/√B

- **Build multivariate discriminant from kinematic variables to separate signal from background in signal-rich regions**

- **Extract signal by simultaneous fit in jet and b-jet multiplicity bins**

8 TeV, 20.3 fb⁻¹
Analysis strategy

- **Event selection**
  - single lepton triggers
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ATLAS Preliminary Simulation
\(\sqrt{s} = 8\) TeV, \(\int L dt = 20.3\) fb\(^{-1}\)

Single lepton
\(m_H = 125\) GeV

Red: signal-rich regions
Blue: signal-depleted regions

Systematics dominated search
Background composition

**single lepton channel**

- $\bar{t}t$+jets - dominant background is both channels (>95% in 3 b-jet regions)
  - $\bar{t}t$+bb - same final state as ttH signal
- modelled with Powheg+Pythia
- top $p_T$ and $\bar{t}t$ $p_T$ reweighted with correction factors obtained from differential cross section measurement at 7 TeV

**dilepton channel**

- $tt+\bar{t}b/c\bar{c}$ model in Powheg+Pythia is comparable to Madgraph (ME-PS MC)
- $tt+\bar{t}b/c\bar{c}$ rate is calibrated to data in the fit using background dominated bins in signal-rich regions
  - 50% normalization uncertainty on $tt+\bar{t}b/c\bar{c}$
  - uncertainties due to generator
    - Powheg+Pythia vs Madgraph+Pythia
  - uncertainties due to parton shower
    - Powheg+Pythia vs Powheg+Herwig
**Background composition**

- **single lepton channel**

  - 4j, 2b
  - 5j, 2b
  - $\geq 6j$, 2b
  - 4j, 3b
  - 5j, 3b
  - $\geq 6j$, 3b
  - 4j, $\geq 4b$
  - 5j, $\geq 4b$
  - $\geq 6j$, $\geq 4b$

  **ATLAS**
  - Preliminary Simulation
  - $m_H = 125$ GeV
  - $\sqrt{s} = 8$ TeV

  - **tt+jets** - dominant background is both channels (>95% in 3 b-jet regions)
    - **tt+bb** - same final state as ttH signal
      - modelled with Powheg+Pythia
      - top $p_T$ and $\bar{t}\bar{t}$ $p_T$ reweighted with correction factors obtained from differential cross section measurement at 7 TeV

- **dilepton channel**

  - 2j, 2b
  - 3j, 2b
  - $\geq 4j$, 2b
  - 3j, 3b
  - $\geq 4j$, 3b
  - $\geq 4j$, $\geq 4b$

  **ATLAS**
  - Preliminary Simulation
  - $m_H = 125$ GeV
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  - **tt+bb/c\bar{c} model in Powheg+Pythia is comparable to Madgraph (ME-PS MC)**
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03/07/2014 E.Shabalina - Search for Higgs in association with top - ICHEP 2014
Signal discrimination

**single lepton channel**

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<td>5 jets</td>
<td>(H_T^{\text{had}})</td>
<td>NN</td>
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<tr>
<td>(\geq 6) jets</td>
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- **Signal-rich regions:** neural network NN trained to separate \(ttH\) from \(tt+\text{jets}\)
  - event shape variables: centrality
  - object pair properties: \(\Delta \eta_{jj}\), \(\Delta \eta\)
  - object kinematics: \(p_T^{\text{jet}\,5}\)
  - event kinematics: \(H_T\), \(N_{p_T>40}\)

- **Dedicated NN** in single lepton channel with 5 jets, 3 \(b\)-jets to separate \(tt+\text{bb/cc}\) from \(tt+\text{light}\)

**dilepton channel**

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**examples of input variables to NN**

\[ C = \sum_{\ell,\text{jets}} \frac{p_T}{\sum_{\ell,\text{jets}} E} \]
Signal discrimination

**single lepton channel**

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**dilepton channel**

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- Signal-rich regions: neural network NN trained to separate $tt\bar{H}$ from $tt+\text{jets}$
  - event shape variables: centrality
  - object pair properties: $\Delta \eta_{jj}$, $\Delta \eta$
  - object kinematics: $p_T^{jet5}$
  - event kinematics: $H_T$, $N_{p_T>40}$

- Dedicated NN in single lepton channel with 5 jets, 3 b-jets to separate $tt+bb/cc$ from $tt+\text{light}$
Signal extracted via binned likelihood fit to 6 signal and 9 control regions under S+B hypothesis

Uncertainties included in the fit via nuisance parameters

Fit reduces background uncertainty by a factor of ~5-6 in most sensitive regions
Background modelling

single lepton channel

before fit

ATLAS Preliminary

before fit

after fit

dileptons channel
**Results**

Combination of single and dilepton channels

95% CL observed (expected) limit:

$$4.1 \times \text{SM} \ (2.6 \times \text{SM}) \text{ for } m_H = 125 \text{ GeV}$$

Best fit: signal strength $\mu = 1.7 \pm 1.4$

ATLAS-CONF-2014-011
□ Combine new $t\bar{t}H(\gamma\gamma)$ with $t\bar{t}H(bb)$
  ‣ Likelihood fit in 19 categories
  ‣ 15 from $t\bar{t}H(bb)$
  ‣ 4 from $t\bar{t}H(\gamma\gamma)$
□ Modifications to $t\bar{t}H(bb)$ result
  ‣ Higgs mass changed to 125.4 GeV
  ‣ Uncertainty on $H\to bb$ branching
  ‣ Theoretical uncertainty on SM $t\bar{t}H$ cross section

\[ \mu_{t\bar{t}H} = 1.2 \pm 2.6 +2.5 -1.7 \]

\[ \mu_{t\bar{t}H} = 1.8 \pm 1.5 -1.4 +0.7 \]

\[ \mu_{t\bar{t}H} = 1.6 \pm 1.3 -1.1 +0.6 \]

95% CL observed (expected) limit:
3.9×SM (2.3×SM) for $m_H = 125.4$ GeV

Best fit: signal strength

\[ \mu_{t\bar{t}H} = 1.6 \pm 0.6(\text{stat.})^{+1.1}_{-1.0}(\text{syst.}) \]

Significance observed (expected): 1.5 $\sigma$ (1.0 $\sigma$)
ATLAS performed searches of $t\bar{t}H$ production using $H\rightarrow\gamma\gamma$ and $H\rightarrow b\bar{b}$ decay modes

- $t\bar{t}H(b\bar{b})$ 95% CL observed (expected) limit: $4.1 \times SM (2.6 \times SM)$
- $t\bar{t}H(\gamma\gamma)$ 95% CL observed (expected) limit: $6.5 \times SM (4.9 \times SM)$
- $t\bar{t}H$ combination 95% CL observed (expected) limit: $3.9 \times SM (2.3 \times SM)$

Search in the $t\bar{t}H$(multilepton) channel and combination of all $t\bar{t}H$ channels is well underway

$t\bar{t}H$ observation and Yukawa coupling measurement is one of the priorities for Run 2 of LHC

- higher energy is advantageous for $t\bar{t}H(b\bar{b})$ observation
  - $t\bar{t}H$ cross section increases by 4.7 while $t\bar{t}$ cross section by 3.7 at 14 TeV