Search for the 125 GeV Higgs boson in the ttH production mode with the ATLAS detector

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The Yukawa coupling $Y_t$ of the Higgs boson to the top quark is a key parameter of the SM.

One of the most direct ways is by measuring the signal strength $\mu$ of the $t\bar{t}H$ production.

$$\mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM} \approx Y_t^2$$

Any significant deviation of $\mu$ from 1 would be a signal for BSM physics.

Results on $\mu$ obtained by the ATLAS collaboration

- in Run I: $\sqrt{s}$ 7-8 TeV, $L_{\text{int}} = 4.5$-20.3 fb$^{-1}$
- in part of Run II: $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 13.3$ fb$^{-1}$

are presented here.

Details on several selected final states will be also given.
A large number of final states has been studied

There are always 2 b-quarks from the 2 top-quark decays. The associated particles are determined

by the Higgs decay:

\[
H \rightarrow bb \ (58.1\%)
\rightarrow WW^* \ (21.5\%)
\rightarrow \tau \tau \ (6.3\%)
\rightarrow ZZ^* \ (2.6\%)
\rightarrow \gamma \gamma \ (0.23\%)
\]

by the decay products of the 2 W’s (from the 2 top-quarks):

\[
W \rightarrow qq \ W \rightarrow qq \ \text{Hadronic (H) channel}
W \rightarrow qq \ W \rightarrow l\nu \ (l = e, \mu) \ \text{Single-lepton (SL) channel}
W \rightarrow l\nu \ W \rightarrow l\nu \ \text{Dilepton (DL) channel}
\]

The signal cross section is calculated to NLO and modelled by MadGraph5_aMC@NLO.
**H \rightarrow bb**

The largest Higgs branching fraction

**SL and DL channels (Run II)**


**SL selection:**

1 l (e,μ) $p_T > 25$ GeV

$N_j \geq 4$, $N_b \geq 2$ $p_T > 25$ GeV

**DL selection:**

2 OS l (ee, eμ, μμ) $p_T^1 > 25$ GeV

$N_j \geq 3$, $N_b \geq 2$ $p_T > 25$ GeV
The dominant background is $tt+nj$, in the signal region $tt+HF\ (b,c)$. It is simulated with POWHEG+Pythia6. $tt+HF$ reweighted to match to Sherpa+OpenLoops NLO 4F calculation. $tt+HF$ normalization and shape was constrained in the final fit. Small instrumental background (mis-identified or non-prompt leptons) estimated from data.
Signal and background are **discriminated** in the SR by MVA (2-stage* BDT) variables.

In the CR we use $\Sigma p_T$ ( $H_T^{\text{had}}$ or $H_T^{\text{all}}$) variables.

* Stage 1: BDT trained on signal to separate correct and false assignment between jets and partons.

2: BDT trained on signal and background to separate signal and background like events.
Uncertainties affecting the value of $\mu$

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} + \geq 1b$ modelling</td>
<td>+0.53</td>
</tr>
<tr>
<td>Jet flavour tagging</td>
<td>+0.26</td>
</tr>
<tr>
<td>$t\bar{t}H$ modelling</td>
<td>+0.32</td>
</tr>
<tr>
<td>Background model statistics</td>
<td>+0.25</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ modelling</td>
<td>+0.24</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.19</td>
</tr>
<tr>
<td>$t\bar{t}$+light modelling</td>
<td>+0.19</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>+0.18</td>
</tr>
<tr>
<td>Jet-vertex association, pileup modelling</td>
<td>+0.12</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.12</td>
</tr>
<tr>
<td>$t\bar{t}Z$ modelling</td>
<td>+0.06</td>
</tr>
<tr>
<td>Light lepton ($e, \mu$) ID, isolation, trigger</td>
<td>+0.05</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.90</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ normalisation</td>
<td>+0.34</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ normalisation</td>
<td>+0.14</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>+0.49</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+1.02</td>
</tr>
</tbody>
</table>

A nuisance parameter is associated to each systematic uncertainty
Distributions of the final discriminating variables from all regions participate in the construction of the profile likelihood ratio test statistics. One derives (i) the observed value of $\mu$ by fitting the nuisance parameters (ii) and the upper limits using the CLs method.

The $tt+\geq 1b$ and $tt+\geq 1c$ normalizations have been fitted to $1.33^{+0.18}_{-0.17}$ and to $1.31^{+0.53}_{-0.40}$, respectively.
**ATLAS Preliminary**

**$t\bar{t}H$ (b\bar{b}), \sqrt{s} = 13$ TeV, $13.2$ fb$^{-1}$**

- **Dilepton**
  - $4.6 \pm 2.3 (1.4, 2.6)$
- **Single Lepton**
  - $1.6 \pm 1.1 (0.5, 1.0)$
- **Combined**
  - $2.1 \pm 1.0 (0.5, 0.9)$

**Best fit $\mu = \sigma^{\rm HH}/\sigma_{\rm SM}^{\rm HH}$ for $m_H = 125$ GeV**

**95% CL limit on $\sigma/\sigma_{\rm SM}(t\bar{t}H)$ at $m_H = 125$ GeV**
H→bb

H channel aka FH (Run I)


Event selection:
Multijet trigger: \( N_j \geq 5 \) with \( p_T > 55 \text{ GeV} \) \( |\eta| < 2.5 \)
Offline: \( N_j \geq 6, N_b \geq 2 \) (60% eff)
e, \( \mu \) veto

High BR of \( W\rightarrow qq \) results in high statistics

Main challenge is the overwhelming multijet (MJ) background

The MJ background is estimated from data.
Using the TRF_{MJ} method a pseudo MJ sample is constructed starting from the \( N_b = 2 \) region of the data.
Validated in the \( N_j = 6 \) (signal depleted) control region.
Applied in the \( N_j \geq 7 \) signal region.
Other backgrounds and signals are simulated by MC similarly to SL and DL.
MVA (BDT) is used to separate the $ttH$ signal from the background.

<table>
<thead>
<tr>
<th>Sources of systematic uncertainty</th>
<th>$\pm 1\sigma$ post-fit impact on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ normalisation</td>
<td>108%</td>
</tr>
<tr>
<td>Multijet normalisation</td>
<td>71%</td>
</tr>
<tr>
<td>Multijet shape</td>
<td>60%</td>
</tr>
<tr>
<td>Main contributions from $t\bar{t}$ modelling</td>
<td>34% – 41%</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>31%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>27%</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>22%</td>
</tr>
<tr>
<td>Luminosity + trigger + JVF + JER</td>
<td>18%</td>
</tr>
</tbody>
</table>

Similar statistical treatment as for the SL and DL channels:

$\mu = 1.6 \pm 0.8 \text{ (stat)} \pm 2.5 \text{ (syst)}$

Systematics dominated
**H → ML (Run II)**


**Small background** in the selected event topologies

Leptonic decays of the W’s and τ’s result in 2, 3, 4 light leptons, \( l = e, \mu \)

Leptons from the top-quark and Higgs can have the same sign (SS)

The final states are re-grouped in the following 4 event categories(*):

\[
\begin{align*}
2(\text{SS})l+0\tau_{\text{had}} & \quad 2(\text{SS})l+1\tau_{\text{had}} & \quad 3l & \quad 4l
\end{align*}
\]

(*): The 2(SS)l+0\tau_{\text{had}} category is subdivided into 3 subcategories: ee, e\mu and \( \mu\mu \)
Event selection:

Single electron or single muon trigger

4 main signal regions (SR)

2(SS)l 0τ_{had}: 2 tight leptons, p_T > 25 GeV
\quad N_j \geq 5, N_b \geq 1

2(SS)l 1τ_{had}: 2 tight leptons, p_T > 25, 15 GeV
\quad N_j \geq 4, N_b \geq 1

3l: Σ Q = ± 1; 2 tight SS leptons, p_T > 20 GeV;
\quad m(OS) > 10 GeV and outside m_Z;
\quad N_j \geq 4, N_b \geq 1 \text{ or } N_j = 3, N_b \geq 2

4l: Σ Q = 0;
\quad m(OS) > 10 GeV and outside m_Z;
\quad 100 < m(4l) < 350 GeV and outside m_H
\quad N_j \geq 2, N_b \geq 1

The main SM backgrounds with prompt leptons: ttW, ttZ and WZ are estimated by MC and validated in regions (VR) which don’t overlap with the SR’s.

Background involving non-prompt leptons and fake τ_{had} candidates are estimated from data in the different SR’s.

Charge misreconstruction is estimated from data by comparing the Z-mass peak for SS and OS ee-pairs.

Signal repartition:

<table>
<thead>
<tr>
<th>Higgs boson decay mode</th>
<th>A × ε (×10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW*</td>
<td>77%</td>
</tr>
<tr>
<td>ττ</td>
<td>17%</td>
</tr>
<tr>
<td>ZZ*</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td>46%</td>
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<tr>
<td></td>
<td>51%</td>
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<tr>
<td></td>
<td>2%</td>
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<tr>
<td></td>
<td>1%</td>
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<tr>
<td></td>
<td>2.2</td>
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<tr>
<td></td>
<td>74%</td>
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<tr>
<td></td>
<td>20%</td>
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<tr>
<td></td>
<td>4%</td>
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<td>2%</td>
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<td></td>
<td>9.2</td>
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<td></td>
<td>72%</td>
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<td></td>
<td>18%</td>
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<td></td>
<td>9%</td>
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<td></td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
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</tbody>
</table>
The dominant systematic error is due to
- non-prompt lepton determination and charge misreconstruction
- jet-vertex association, pile-up modeling

The observed values of $\mu$ and its upper limits are derived by the same statistical method as outlined in the $ttH \rightarrow bb$ case

**Event yields**

**SR**
**H → γγ (Run II)**

Excellent di-photon resolution but suffers from the small decay BR

**Event selection**: 2 isolated photons with $E_T > 25$ GeV

**Leptonic ttH category:**
- $N_l \geq 1$, $N_j \geq 2$ and
- $N_b \geq 2$ or $N_b \geq 1$ and MET $> 20$ GeV

**Hadronic ttH category:**
- $N_j \geq 5$ ($p_T > 30$ GeV) with $N_b \geq 1$

$$\mu = -0.3^{+1.2}_{-1.0} \text{ (tot.)} \, [\, +1.2_{-1.0} \text{ (stat.)}]$$
Significant improvement is expected soon:
Run II sensitivity already outperforms that of Run I and 
~2x more statistics in Run II is available

Combination with CMS: \( \mu = 2.3 \pm 0.7 - 0.6 \)
Bonus slides
The ATLAS general purpose detector
The semi-frequentist or CLs method

Log-Likelihood-Ratio (LLR) as test statistics:

\[ \text{LLR} = -2 \ln \frac{P(N|H_1)}{P(N|H_0)} \]

\( H_0 \) and \( H_1 \) - test hypotheses of background w/o and w/ signal
\( N \) - number of events of the ensemble with expected number \( \alpha(\theta) \)
\( P \) - Poissonian pdf of \( N \):
\[ P = e^{-\alpha} \frac{\alpha^N}{N!} \]
includes pdf of nuisance parameters \( \theta \):
\[ \exp\left[-\frac{(\theta - \theta_0)^2}{2\sigma_\theta^2}\right] \]

Profiling:
LLR is minimized wrt the nuisance parameters \( \theta \)

\[ \text{LLR}_{\text{obs}} = \text{LLR}(N=\text{Data}) \]
\[ \text{LLR}_b = \text{LLR}(N=\text{Background}) \]
\[ \text{LLR}_{sb} = \text{LLR}(N=\text{Signal+Background}) \]

Confidence levels:
1-CLb = \( p(\text{LLR}_b<\text{LLR}_{\text{obs}}|H_0) \)
CLsb = \( p(\text{LLR}_{sb} > \text{LLR}_{\text{obs}}|H_1) \)
CLs = CLsb/CLb

A signal \( \mu \) is excluded @ 95% CL if \( \text{CL}_s(\mu) = 0.05 \) i.e. 1-CLs(\( \mu \)) = 0.95
The MJ Tag Rate Function (TRF\textsubscript{MJ}) method

- Take a data (MC) sample obtained by a MJ (di-jet) trigger
- Select events with \( N_b \geq 2 \)
- Consider in all events all jets except the 2 b-tagged jets with the highest b-tag probability \((b_1, b_2)\)
- Determine from those jets the probability \( \varepsilon_b \) (aka TRF\textsubscript{MJ}) that a jet is b-tagged as a function of \( p_T, |\eta| \) and its distance (\( \Delta R \)) from \( b_1 : \varepsilon_b = n_b(p_T, |\eta|, \Delta R)/n_j(p_T, |\eta|, \Delta R) \)
- Take a subsample with \( N_b = 2 \) and using \( \varepsilon_b \) calculate the probability \( w \) that an event will contain \( N_b \geq 2 \)
- Apply \( w \) as event weight and promote jets as b-tagged using \( \varepsilon_b \) to obtain the desired pseudo MJ sample
- To validate the method one compares the pseudo sample with the original sample of \( N_b > 2 \).
ttH→bb FH channel

BDT responses normalized to the same surface

Event yield wrt log_{10}(S/B)
Significance of the $ttH$ production in Run II

$\text{Significance} = \sqrt{-2 \Delta \ln L(\mu=0)} \sigma$

$= 2.8 \sigma$ for the combination