Measurements and searches of Higgs boson decays to two fermions and of Higgs boson production in association with a ttbar pair at the ATLAS experiment

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6/5/2019
Testing the couplings of the Higgs boson to fermions

$H \rightarrow$ fermions represent $\sim 70\%$ of the Higgs decays.

Outline:

- coupling to third generation fermions:
  - $t\bar{t}H$, $H \rightarrow b\bar{b}$, $H \rightarrow \tau\tau$
- going beyond, simplified template cross section
  - reinterpretation of $VH, H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$
- searches for couplings with second generation fermions
  - $H \rightarrow c\bar{c}$, $H \rightarrow \mu\mu$
- searches for lepton-flavour-violating decays
Couplings to third generation fermions

- Measurements of the Higgs coupling to fermions can provide stringent tests of the validity of the SM.
- only coupling to third generation fermions can be currently measured

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**t\bar{t}H** production

\[ m_H = 125 \text{ GeV} \Rightarrow \text{Higgs to top coupling studied in the associated production} \]

Most favorable production mode for **direct measurement** of top Yukawa coupling

- **Complexity:** \(t\bar{t}H\) two orders of magnitude smaller than total Higgs cross section
- **Advantage:** distinctive top signature, access to many Higgs decays
Observation of $t\bar{t}H$ with up to 80 fb$^{-1}$

Combination of:
- $H \rightarrow b\bar{b}$ with 36 fb$^{-1}$
- $H$ multilepton ($WW^*, \tau\tau, ZZ^*$) with 36 fb$^{-1}$
- $H \rightarrow \gamma\gamma$ with 80 fb$^{-1}$
- $H \rightarrow ZZ^* \rightarrow 4l$ with 80 fb$^{-1}$

Combination with $t\bar{t}H$ searches at 7 TeV and 8 TeV: 6.3σ (5.1 expected) → **direct observation** of Yukawa coupling between Higgs and top

> arXiv:1806.00425
$t \bar{t} H$ in multilepton final states with 36 fb$^{-1}$

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

Events split in seven channels according to the number of selected light leptons and $\tau_{had}$ candidates.

**Significance**: $4.1\sigma$ (expected $2.8\sigma$)

[Graph showing the split of events into seven channels based on the number of selected light leptons and $\tau_{had}$ candidates.]

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**ATLAS**

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<thead>
<tr>
<th>Number of $\tau_{had}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
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<tr>
<td>SS</td>
<td>2</td>
<td>1+2 $\tau_{had}$</td>
<td>2+SS+1 $\tau_{had}$</td>
<td>3+1 $\tau_{had}$</td>
<td>4$\ell$</td>
</tr>
<tr>
<td>OS</td>
<td>2+SS</td>
<td>2+OS+1 $\tau_{had}$</td>
<td>3+1 $\tau_{had}$</td>
<td>4$\ell$</td>
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**Best-fit $\mu_{t\bar{t}H}$ for $m_H=125$ GeV**

- $2\ell$ OS + 1 $\tau_{had}$: 1.7 $\pm$ 0.6 $\pm$ 0.5
- $1\ell$ + 2 $\tau_{had}$: 1.0 $\pm$ 0.6 $\pm$ 0.5
- $3\ell$ + 1 $\tau_{had}$: 1.6 $\pm$ 0.6 $\pm$ 0.5
- $2\ell$ SS + 1 $\tau_{had}$: 1.5 $\pm$ 0.6 $\pm$ 0.5
- $3\ell$: 1.8 $\pm$ 0.6 $\pm$ 0.5
- $2\ell$ SS: 1.5 $\pm$ 0.6 $\pm$ 0.5
- Combined: 1.6 $\pm$ 0.4 $\pm$ 0.3

**$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$**

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* Higgs couplings to fermions
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[*arXiv:1712.08891*]
ttH, $H \rightarrow \gamma\gamma$ with $139 \text{ fb}^{-1}$, New!

- One of the first publications with full Run II dataset!
- Only $80 \text{ fb}^{-1}$ result included in combination

BDT trained using the $E_T^{\text{miss}}$, photons, leptons and jets kinematic variables and the jets b-tag status.

Two regions with dedicated BDT
- "Lep" region with at least a W decaying leptonically
- "Had" region for hadronic top decays

Events are further categorised according to the BDT score

4.9σ observed (4.2σ expected)
\( t\bar{t}H, \ H \rightarrow b\bar{b} \) with 36 fb\(^{-1}\)

- one or both top decaying semi-leptonically
- multivariate techniques

Events categorisation:
- number of leptons (one or two)
- number of jets (3 to 6)
- number of b-jets at 4 working points

Dedicated "boosted" category for high energy events
1.4\(\sigma\) observed (1.6\(\sigma\) expected) ▶ arXiv:1712.08895

dominated by systematic uncertainties (theoretical knowledge of one of the main background, \(t\bar{t}+ \geq 1b\))
**VH, \( H \rightarrow b\bar{b} \) with 80 fb\(^{-1}\)**

Large BR (\( \sim 58\% \)) but large multi-jet background \( \Rightarrow \) study \( H \rightarrow b\bar{b} \) decay in associated production \( VH, H \rightarrow b\bar{b} \)

Three selection channels
- 0 leptons: \( ZH \rightarrow \nu\nu b\bar{b} \)
- 1 lepton: \( WH \rightarrow \ell\nu b\bar{b} \)
- 2 leptons: \( ZH \rightarrow \ell\ell b\bar{b} \)

BDT trained in all signal regions and used as final discriminant \( \text{arXiv:1808.08238} \)
$H \rightarrow b\bar{b}$ in vector boson fusion production with 31 fb$^{-1}$

Complementary to $VH$ production

Three channels considered:
- all hadronic channels:
  - two central jets
  - four central jets
- a photon associated channel

Upper limit on $\sigma \times BR \Rightarrow 4.8$ times the SM expectation for inclusive production ($2.5^{+1.0}_{-0.7}$ expected) and 5.9 for VBF ($3.0^{+1.3}_{-0.8}$ expected)

arXiv:1807.08639
**VH, $H \rightarrow b\bar{b}$ combination**

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<th>Process</th>
<th>Total</th>
<th>Stat.</th>
<th>$\sigma_{\text{measured}}$ with uncertainties</th>
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<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>1.68</td>
<td>+1.16 -1.12</td>
<td>+1.01 0.57 -1.00 0.51</td>
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<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>0.94</td>
<td>+1.30 -0.87</td>
<td>+1.26 0.32 -0.85 0.14</td>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>1.03</td>
<td>+0.60 -0.54</td>
<td>+0.53 0.28 -0.50 0.22</td>
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<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>1.17</td>
<td>+0.27 -0.25</td>
<td>+0.16 0.21 -0.16 0.19</td>
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**Comb.**

$H \rightarrow b\bar{b}$ observation

$VH$ observation

$$\mu = \frac{\sigma_{\text{measured}}}{\sigma_{\text{expected (SM)}}}$$

-arXiv:1808.08238-

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Higgs couplings to fermions

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$H \rightarrow \tau \tau$ with $36 \text{ fb}^{-1}$

- $\text{BR} \sim 6\%$
- only currently accessible leptonic decay mode

All combinations of leptonic and hadronic tau decays considered

Combination of results at $\sqrt{s} = 13 \text{ TeV}$ with results at 7 and 8 TeV:

6.4$\sigma$ observed (5.4$\sigma$ expected)

arXiv:1811.08856
Going beyond, Simplified Template Cross Sections

Proposed at Les Houches 2015

Measure production modes cross-sections \((ggF, VBF, VH, ttH)\) in exclusive regions defined in fiducial selection \(\rightarrow\) reduced model dependency and maximised sensitivity to BSM effects

**Goals**

- probe Higgs properties in more detail
- reduced extrapolation from analysis selection phase space to measurement phase space
- easier to compare with future updated calculations
- easy combination of different decay channels \(\rightarrow\) increase sensitivity
**VH, H → b¯b in STXS framework with 80 fb$^{-1}$**

Possibility to go beyond the signal strength measurement → STXS

Beyond the Standard Model (BSM) effects parameterised with an effective lagrangian. STXS measurements set limits on the lagrangian parameters

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} O_i^{(6)} \]

In \( H \rightarrow \tau \tau \) a three-dimensional fit was performed in the STXS framework (VBF cross section in one region and ggF cross sections in two exclusive regions of phase space)

arXiv:1903.04618, theoretical uncertainties evaluation

arXiv:1811.08856
Couplings to second generation fermions

- couplings to **second generation** fermions expected to be much smaller w.r.t third generation fermions
- some BSM scenarios predict deviations of 2nd generation couplings as the Yukawa coupling is so small

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$H \rightarrow c\bar{c}$ with 36 fb$^{-1}$

Challenging measurement at hadron colliders

- small branching fraction ($\sim 3\%$)
- large backgrounds → study the associated production $ZH \rightarrow l^+ l^- c\bar{c}$
- challenging c-tagging

Observed upper limit on $\sigma(pp \rightarrow ZH) \times B(H \rightarrow c\bar{c})$ is 2.7 pb
(expected SM value: 26 fb)  

arXiv:1802.04329
$H \rightarrow \mu\mu$ with 80 fb$^{-1}$

- $\text{BR}(H \rightarrow \mu\mu) \sim 2.2 \times 10^{-4} \Rightarrow$ rare decay but clear signature
- Only way to directly measure couplings between a Higgs boson and second generation fermions at LHC

Events split with MVA discriminant to target VBF and ggF production

Observed upper limit on $\sigma \times BR \Rightarrow 2.1$ times the SM prediction.
Dominated by statistical uncertainty

\[\text{ATLAS-CONF-2018-026}\]
Higgs lepton-flavour-violating decays with 36 fb\(^{-1}\), new!

Search for \(H \rightarrow e\tau\) and \(H \rightarrow \mu\tau\)

No significant excesses over the SM predictions observed (expected) 95% CL upper limits on the branching ratios

- \(H \rightarrow e\tau\) 0.47\% (0.34\(^{+0.13}_{-0.10}\)\%)
- \(H \rightarrow \mu\tau\) 0.28\% (0.37\(^{+0.14}_{-0.10}\)\%)

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Conclusions

Many important results reached:

- observation of $H \rightarrow bb$
- observation of $VH$ production
- observation of $ttH$ production
- observation of $H \rightarrow \tau\tau$

First results within the simplified template cross section framework

- $VH$ with $H \rightarrow bb$
- VBF and ggF with $H \rightarrow \tau\tau$

All results seem to agree to SM predictions

Many of the analysis presented are statistically limited

→ stay tuned for the full Run II results (140 fb$^{-1}$)!