Studying the top quark-Higgs boson coupling at ATLAS

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Cornell Journal Club, 29 Apr 2016
Fermion Masses

• Want to check whether fermion mass generation mechanism is that of SM
  - a priori EWSB is a different problem

• SM Higgs couples $\propto$ to fermion mass, decay rate $\propto$ mass$^2$
  - only interactions with the heaviest fermions are observable

• Assuming generation independence ... need to constrain
  - $H \rightarrow$ leptons: $H \rightarrow \tau\tau$
  - $H \rightarrow$ down-type fermions: $H \rightarrow bb$, $H \rightarrow \tau\tau$
  - $H \rightarrow$ up-type fermions: $pp \rightarrow ttH$, $pp \rightarrow H$ (gluon-gluon fusion)

• Higgs boson may have other couplings to the top quark than the SM ones
How to measure the ttH Coupling?

- Highest rate way: $g g \rightarrow H$ through top loop
- However effects of top are not distinguishable from new physics in $g g \rightarrow H$ or $qq \rightarrow H$
- A tree-level measurement is possible: $pp \rightarrow t\bar{t}H$
Constraints on Higgs Couplings

- Need ttH to simultaneously constrain top coupling and new physics in ggF loop

ATLAS-CONF-2014-009
outdated – for illustration...

SM particles only

\begin{align*}
\text{ATLAS Preliminary} & \quad \text{Total uncertainty} \\
m_H = 125.5 \text{ GeV} & \quad \pm 1\sigma \quad \pm 2\sigma
\end{align*}

- $\kappa_Z = 0.95^{+0.24}_{-0.19}$
- $\kappa_W = 0.68^{+0.30}_{-0.14}$
- $\kappa_t \in [-0.80, -0.50] \cup [0.61, 0.80]$
- $\kappa_b \in [-0.7, 0.7]$
- $\kappa_\gamma \in [-1.15, -0.67] \cup [0.67, 1.14]$

Allowing new particles in loops

\begin{align*}
\text{ATLAS Preliminary} & \quad \text{Total uncertainty} \\
m_H = 125.5 \text{ GeV} & \quad \pm 1\sigma \quad \pm 2\sigma
\end{align*}

- $\lambda_{\gamma\gamma} = 1.02^{+0.17}_{-0.14}$
- $|\lambda_{WW}| = 0.80^{+0.15}_{-0.14}$
- $|\lambda_{bb}| = 0.3^{+0.4}_{-0.3}$
- $|\lambda_{\gamma Z}| = 0.90^{+0.22}_{-0.18}$
- $|\lambda_{gZ}| = 0.73^{+0.22}_{-0.16}$
- $|\lambda_{t\gamma}| = 0.0^{+2.2}_{-0.0}$
- $|\kappa_{gZ}| = 1.18^{+0.17}_{-0.16}$

1s = 7 TeV $\int L dt = 4.6-4.8 \text{ fb}^{-1}$
1s = 8 TeV $\int L dt = 20.3 \text{ fb}^{-1}$
Explicit example of degeneracy between dim-6 operators affecting $pp \rightarrow H$ and $pp \rightarrow ttH$

Higgs-gluon coupling:

$$O_{HG} = \frac{c_{HG}}{2\Lambda^2} (H^\dagger H) G_\mu^\nu G_\mu^\nu$$

Top chromomagnetic dipole:

$$O_{hgt} = \frac{c_{hgt}}{\Lambda^2} (\bar{Q}_L H) \sigma^{\mu\nu} T^a t_R G_\mu^\nu$$

Blue band shows constraint from ggF

Bramante, Delgado, Martin PRD 89, 093006 (2014)
And other new physics ...

- We do a very careful study of phase space rarely covered by new physics searches
  - high multiplicity but not super-high energy/missing transverse energy events

- Potential sensitivity to scenarios like compressed spectra

```
    m

produced
------
      ↓

invisible
------
      ↓

“traditional” cascade
high momentum visible particles
large MET

produced
------
      ↓

invisible
------
      ↓

“compressed” cascade
low momentum visible particles
small MET
```
Process xsec

- Rarest “major” production process – but distinct signature

~ 130 fb @ 8 TeV
Finding $ttH$

- Signature is top pair decay + Higgs decay
- Top quarks decay $\sim 100\%$ via $t \rightarrow W \, b$
  - $W$ decays $68\%$ of the time to quarks, $\sim 11\%$ to each of $e$, $\mu$, $\tau$
- Top quark pair can be dileptonic, semileptonic ("lepton+jets"), or all hadronic
  - dileptonic with $e$ and $\mu$ $\sim 4\%$ of $t\bar{t}$ decays
  - all hadronic must be separated from pure QCD multijet events
H → γγ gives clean Higgs tag, can use mass sidebands. Channel so clean that main challenge is contamination from other Higgs production modes

- A bump at 125 GeV is a Higgs: but is it ttH?

Split by top pair decays:

- lepton + jets: lepton and b-tag requirement enough to remove all other major Higgs production mechanisms
- all hadronic: contaminated by gluon-gluon fusion. Strict cuts applied to improve purity of observed signal

<table>
<thead>
<tr>
<th>Category</th>
<th>NH</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>t(t)H</th>
<th>tHqb</th>
<th>WtH</th>
<th>NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV leptonic selection</td>
<td>0.10</td>
<td>0.6</td>
<td>0.1</td>
<td>14.9</td>
<td>4.0</td>
<td>72.6</td>
<td>5.3</td>
<td>2.5</td>
<td>0.5+0.3-0.3</td>
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<tr>
<td>7 TeV hadronic selection</td>
<td>0.07</td>
<td>10.5</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
<td>80.9</td>
<td>2.6</td>
<td>1.9</td>
<td>0.5+0.3-0.3</td>
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<tr>
<td>8 TeV leptonic selection</td>
<td>0.58</td>
<td>1.0</td>
<td>0.2</td>
<td>8.1</td>
<td>2.3</td>
<td>80.3</td>
<td>5.6</td>
<td>2.6</td>
<td>0.9+0.6-0.4</td>
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<tr>
<td>8 TeV hadronic selection</td>
<td>0.49</td>
<td>7.3</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
<td>84.2</td>
<td>3.4</td>
<td>2.1</td>
<td>2.7+0.9-0.7</td>
</tr>
</tbody>
</table>
Diphoton Results

Set $\mu_{\text{non-ttH}} = 1$

<table>
<thead>
<tr>
<th></th>
<th>Observed limit</th>
<th>Expected limit</th>
<th>$+2\sigma$</th>
<th>$+1\sigma$</th>
<th>$-1\sigma$</th>
<th>$-2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined (with systematics)</td>
<td>6.7</td>
<td>4.9</td>
<td>11.9</td>
<td>7.5</td>
<td>3.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Combined (statistics only)</td>
<td>6.3</td>
<td>4.7</td>
<td>10.5</td>
<td>7.0</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Leptonic (with systematics)</td>
<td>10.7</td>
<td>6.6</td>
<td>16.5</td>
<td>10.1</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Leptonic (statistics only)</td>
<td>10.2</td>
<td>6.4</td>
<td>15.1</td>
<td>9.6</td>
<td>4.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Hadronic (with systematics)</td>
<td>9.0</td>
<td>10.1</td>
<td>25.4</td>
<td>15.6</td>
<td>7.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Hadronic (statistics only)</td>
<td>8.5</td>
<td>9.5</td>
<td>21.4</td>
<td>14.1</td>
<td>6.8</td>
<td>5.1</td>
</tr>
</tbody>
</table>
tH

- SM has destructive interference between H emission from top and from W: if relative sign of top coupling flips, have large constructive interference

- Can resolve relative sign of fermionic and bosonic Higgs couplings
  - interplay with Br(H → γγ), which also depends on HWW/Ht̅t̅ interference

\[ -2\Delta\ln(L) \]

**ATLAS**
2011-2012

\[ L_{dt} = 4.5 \text{ fb}^{-1}, \ \sqrt{s} = 7 \text{ TeV} \]

\[ L_{dt} = 20.3 \text{ fb}^{-1}, \ \sqrt{s} = 8 \text{ TeV} \]

\[ m_H = 125.4 \text{ GeV} \]
H → bb

- H → bb is 58% of the SM Higgs width at 125 GeV
  - Mass resolution is much worse than for γγ
  - Background (tt + heavy flavor jets) tricky to model

- Strategy: sort events by number of jets and b-tags, then in each channel use a multivariate discriminant
  - use background-rich channels to constrain background and detector systematics

- Have used lepton+jets, dilepton, and all-hadronic channels (new!)
  - talk about the leptonic channels first, then allhad

EPJ C 75, 349 (2015) (l+jets, dilep)
arxiv:1604.03812 (allhad)
Backgrounds

- leptonic channels: dominated by $tt +$ heavy flavor jets in all signal-rich regions

![Pie charts showing background contributions in various channels](chart.png)
To improve agreement of MC and data, **reweight** the $t\bar{t}$ pair $p_T$ and the top quark $p_T$ with scalings derived from 7 TeV data

- Powheg+Pythia spectra generally too hard
- $t\bar{t}$+light, $t\bar{t}$+cc events only; $t\bar{t}$+bb handled differently

*top kinematics: JHEP 06(2015) 100*
• Powheg+Pythia $tt+bb$ reweighted to shower-matched NLO calculation of Sherpa+OpenLoops
  – particular attention paid to separation of $b$ quarks
• Provides theoretically-motivated systematics (Sherpa scale, PDF, shower variations)
NN construction

- Variables that are well modeled in background-dominated channels are used to construct neural network discriminants (with NeuroBayes)
  - even in signal-rich channels, checked modeling after applying anti-NN cut (“partial unblinding”)
- lepton+jets 6-jet channels also have matrix element discriminant

<table>
<thead>
<tr>
<th>lepton + jets</th>
<th>dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>2b</td>
<td>2b</td>
</tr>
<tr>
<td>3b</td>
<td>3b</td>
</tr>
<tr>
<td>4b</td>
<td>4b</td>
</tr>
<tr>
<td>4j</td>
<td>H_{T}^{\text{had}}</td>
</tr>
<tr>
<td>5j</td>
<td>H_{T}^{\text{had}}</td>
</tr>
<tr>
<td>6j</td>
<td>H_{T}^{\text{had}}</td>
</tr>
</tbody>
</table>

† trained for tt+HF vs tt+LF
NN Variable Separation

- Four highest ranked variables shown

\[ D_1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + 0.23 \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}} \]

I+jets $\geq 6j \geq 4b$

dilepton $\geq 4j \geq 4b$

*matrix element*

*Fox-Wolfram moment*
Variable Modeling

l+jets ≥6j ≥4b
dilepton ≥4j ≥4b
Fit effect on Signal-Rich Regions

Profile fit collapses systematics – large correlations
Fit Results

**ATLAS** \( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1}\), \( m_H = 125 \) GeV

- \( t\bar{t}+b\bar{b} \) normalisation
- Jet energy scale 1
- \( t\bar{t}+c\bar{c} \) normalisation
- \( t\bar{t}+b\bar{b} \) renormalisation scale choice \( m_{bb} \)
- \( t\bar{t}+V \) cross section
- \( t\bar{t}+b\bar{b} \) shower recoil scheme
- Jet energy scale 2
- Light-jet tagging 1
- \( t\bar{t}+c\bar{c} \) \( p_T \) reweighting
- \( b \)-jet tagging 1
- \( t\bar{t}+c\bar{c} \) top \( p_T \) reweighting
- \( t\bar{t}+b\bar{b} \) renormalisation scale
- Jet energy scale 3
- Light-jet tagging 2
- \( t\bar{t}+b\bar{b} \) PDF (MSTW)

**Data**
- \( t\bar{t}H (\mu_{\text{fit}}=1.5) \)
- \( t\bar{t}H (\mu_{95\% \text{ excl.}}=3.4) \)
- Bkgd

\( \sqrt{s}=8 \) TeV, 20.3 fb\(^{-1}\)

Combined

Single lepton and Dilepton
ttH[bb] all-hadronic

- Expect events with $\geq 8$ jets, of which $\geq 4$ b-tagged
  - acquire events with multijet triggers
- Multijet backgrounds critical in all categories
  - need data-driven model for MJ properties
- Proceed as per leptonic channels: coupled fit of BDT distributions in each category, same systematic treatment
top-Higgs coupling at ATLAS

- Bootstrap multijet distributions with high # b-jets from regions with low # b-jets
- Take low #b-jet events and assign b-jet probabilities based on $p_T$, $\eta$, distance from other b-jets
  - e.g. more likely to be a b-jet if near another b-jet
• A number of event shape and object variables are used (e.g. centrality, $M(bb)$ for closest $b$-jet pair, ...)

• Also a simple “likelihood” variable $\Lambda$ is used to distinguish events with peaking $m_W$, $m_{\text{top}}$, $m_{\text{Higgs}}$ from combinatorics
ttH[bb] Results

- Combined obs (exp) limit 3.3 (2.1) x SM
  - median limit with SM signal = 3.0 x SM
- Best fit rate (1.4 ± 1.0) x SM
- Many systematics (e.g. tt+HF normalization) will be reduced with more data

![Graph showing 95% CL limit on μ for m_H = 125 GeV](chart.png)
![Graph showing best fit μ for m_H = 125 GeV](chart2.png)
**ttH, H → WW/ττ**

- **Complex topologies: WWWWbb or ττWWbb**
  - rich set of final states with high multiplicities
  - backgrounds mostly tt + EWK, not tt + QCD

- **Take advantage of final states not reachable from tt production**
  - $\geq 3$ leptons, or 2 same sign leptons

- **H → ττ worth exploiting**
  - $\sigma$(ttZ) and $\sigma$(ttH) similar: no overwhelming Z bkg to H → ττ

<table>
<thead>
<tr>
<th>Higgs boson decay mode</th>
<th>WW*</th>
<th>ττ</th>
<th>ZZ*</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 $\ell$ same sign 0τ</td>
<td>80%</td>
<td>15%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>3 $\ell$</td>
<td>74%</td>
<td>15%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>2 $\ell$ same sign 1τ</td>
<td>35%</td>
<td>62%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>4 $\ell$</td>
<td>69%</td>
<td>14%</td>
<td>14%</td>
<td>4%</td>
</tr>
<tr>
<td>1 $\ell$ 2τ</td>
<td>4%</td>
<td>93%</td>
<td>0%</td>
<td>3%</td>
</tr>
</tbody>
</table>

*PLB 749, 519 (2015)*
ttH multilepton decays

Signal

<table>
<thead>
<tr>
<th>Higgs decay</th>
<th>H → WW → ℓνℓν</th>
<th>H → WW → ℓvjj</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H → T_l T_l</td>
<td>H → T_l T_h</td>
</tr>
<tr>
<td></td>
<td>H → T_h T_h</td>
<td></td>
</tr>
</tbody>
</table>

| H → ZZ not very important due to low BF and Z vetoes |

<table>
<thead>
<tr>
<th>tt decay</th>
<th>ℓνℓν bb</th>
<th>ℓvjj bb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4ℓ</td>
<td>3ℓ</td>
<td></td>
</tr>
<tr>
<td>3ℓ</td>
<td>2ℓ0τ</td>
<td></td>
</tr>
<tr>
<td>(4ℓ)</td>
<td>3ℓ</td>
<td></td>
</tr>
<tr>
<td>3ℓ</td>
<td>2ℓ1τ</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>1ℓ2τ</td>
<td></td>
</tr>
</tbody>
</table>

all-hadronic top not targeted

only accept same sign ℓ

+ require ≥1 b-jet, high (≥2-5) jet multiplicity

Backgrounds

Main bkg: non-prompt leptons, ttZ, ttW, diboson + jets, fake τ

- non-prompt lepton bkg estimated from extrapolation in isolation, ID variables, p_T
- other backgrounds estimated from Monte Carlo, checked in various validation regions

Signal

ttZ VR

3 ℓ SR but Z veto inverted

inv mass, smallest ΔR OS lepton pair

2 ℓ SS + 2,3 j (2b)
Fake Lepton Backgrounds

- Slightly different techniques in each channel.
  - $2\ell 0\tau$, $3\ell$, $2\ell 1\tau$: variants on “fake factor” methods
  - $4\ell$: limit from MC
  - $1\ell 2\tau$: predict fake $\tau$ bkg from MC (well modeled with looser event cuts)

Control region cuts, “sideband” lepton
Control region, tight lepton

Signal region cuts, “sideband” lepton

measure/validate fake factor $\theta$

use same $\theta$

e.g. $2\ell 0\tau$: control region cuts: lower # jets than SR
sideband leptons: non-isolated electrons, low-$p_T$ muons

Fake predictions cross checked with other ATLAS methods
**ttH, H → WW/ττ**

### 2 same sign leptons, no tau

#### 2ℓ0τ category

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Total bkg</th>
<th>SM H(125)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Prompt</td>
<td>1.4 ± 0.6</td>
<td>0.47 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>ttW</td>
<td></td>
<td>0.55 ± 0.17</td>
<td>1</td>
</tr>
<tr>
<td>τW</td>
<td></td>
<td>0.20 ± 0.01</td>
<td>10</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

#### 3ℓ category

<table>
<thead>
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<th>Phenomenon</th>
<th>Total bkg</th>
<th>SM H(125)</th>
<th>Observed</th>
</tr>
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<td>τW</td>
<td></td>
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<td>10</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

### 3 leptons

#### ≥ 4 jets, ≥ 1 b-jet or = 3 jets, ≥ 2 b-jets

<table>
<thead>
<tr>
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<tr>
<td>Observed</td>
<td></td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
Combined multilepton channels:

\[ \mu = 2.1^{+1.4}_{-1.2} \]

\[ \mu < 4.7 \text{ obs } (2.4 \text{ exp}) @ 95\% \text{ CL} \]

Consistent with SM

Leading systematics:
non-prompt lepton rate in 2\ell 0\tau
acceptance for ttW+jets
cross sections for ttW, ttZ
Full ttH Combination

- Best fit $\mu = 1.7 \pm 0.8$ (all analyses)
  - $\mu < 3.1$ (1.4 exp) @ 95% CL
- Can perform coupling analysis entirely using ttH channels
  - assume fermions share common Higgs coupling strength modifier $\kappa_F$, bosons share modifier $\kappa_V$
  - compatible with SM

\[ \text{at \ arxiv:1604.03812} \]
ttH Prospects in Run 2

- Each fb\(^{-1}\) worth more @ 13 TeV
  - \(\sigma(ttH)\) up a factor ~ 4
- new pixel layer, b-tagging algorithm improvements give better mistag rate
- Analysis improvements

ttH observation at 5\(\sigma\) is very likely in Run 2 after combination of channels
Flavor-Changing Neutral Currents

- In the SM, there are no vertices involving the Higgs and two different fermions
  - such interactions generally strongly constrained by low energy precision measurements ... except for the third generation
- A detectable tqH (q=u, c) coupling is still allowed
  - if one assumes the tqH coupling is the geometric mean of the ttH and qqH couplings, BR(t → Hc) ~ 0.2%!

\[ \lambda_{tc} = \frac{\sqrt{m_t m_c}}{\nu} \sim 0.063 \]

Fritzsch-like ansatz:

Kao, Cheng, Hou, Sayre
PLB 716, 225 (2012)
FCNC $t \rightarrow Hq$

- Dedicated ATLAS studies done in $H \rightarrow \gamma\gamma$, $H \rightarrow bb$; we also repurposed the $ttH[WW/\tau\tau]$ search
  - challenge: FCNC signal contaminates regions used for non-prompt lepton estimation
  - lesson: new physics will not necessarily restrict itself to search regions

Combination of channels:
Limit $BR(t \rightarrow Hc) < 0.46\%$ (0.25\% exp) @ 95\% CL
Best-fit $BR(t \rightarrow Hc) = (0.22 \pm 0.14)\%$

*JHEP 12(2015) 061*
Summary

- **ttH** is a key channel to measure the top Yukawa coupling and constrain new physics
  - Multiple channels are available to search for the signal
  - discovery will be from combination, not from a single channel
  - Run 1 analyses done, look forward to increased statistics of Run 2!

- Can also look for non-SM-like couplings
  - t → Hc search entering interesting region and is very exciting for Run 2
ttH 2ℓ 1τ candidate
Extra
How to look for $ttH$?

- Generic signature is top pair + a Higgs decay
  - $H \rightarrow \gamma\gamma$ has a narrow bump
  - $H \rightarrow bb$ has a large rate
  - $H \rightarrow WW, H \rightarrow \tau\tau$ produce multilepton events
  - $H \rightarrow ZZ \rightarrow 4\ell$ has too low a rate

- Top pairs have a characteristic signatures of leptons, jets, and b-tagged jets
**[8 TeV] Diphoton Selection**

- **trigger:** diphoton, $p_T > (35, 25)$ GeV
- **photons:** leading (subleading) $p_T > 0.35 (0.25) \times m_{\gamma\gamma}$; require $== 2$ photons
- **leptons:** $e$ $p_T > 15$ GeV; $\mu$ $p_T > 10$ GeV
- **leptonic channel:** $\geq 1$ lepton, $M(e\gamma)$ not in $[84, 94]$ GeV, $\geq 1j @ 25$ GeV, $\geq 1b @ 80\%$ WP, $E_{Tmiss} > 20$ GeV if only one b-jet
- **hadronic channel:** no leptons
  - $\geq 6j @ 25$ GeV, $\geq 2b @ 80\%$ OR
  - $\geq 5j @ 30$ GeV, $\geq 2b @ 70\%$ OR
  - $\geq 6j @ 30$ GeV, $\geq 1b @ 60\%$

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<td>0.6</td>
<td>0.1</td>
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Diphoton Coupling Interpretation

\[ \kappa_t \text{ scales the SM Yukawa coupling (1=SM)} \]
Categories

**ATLAS Simulation**

| $\sqrt{s} = 8 \text{ TeV, 20.3 fb}^1$ | Single lepton  
$m_H = 125 \text{ GeV}$ |
<table>
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<td>$4j, 2b$</td>
<td>$S/B &lt; 0.1%$</td>
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<td>$5j, 2b$</td>
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</tr>
<tr>
<td>$\geq 6j, 2b$</td>
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**ATLAS Simulation**

| $\sqrt{s} = 8 \text{ TeV, 20.3 fb}^1$ | Dilepton  
$m_H = 125 \text{ GeV}$ |
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**ATLAS Simulation**

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<tr>
<td>$\geq 4j, 2b$</td>
</tr>
</tbody>
</table>

S/B improved with neural net
Event Selection

- trigger: single lepton triggers (e or $\mu$); full efficiency @ 25 GeV
- leptons: leading $p_T > 25$ GeV, subleading $p_T > 15$ GeV (dilepton channel)
  - 1, 2-lep channels have no overlap
  - dilepton: $M_{ll} > 15$ GeV, veto events with $M_{ll} = M_Z \pm 8$ GeV for same flavor; $H_T > 130$ GeV for $e\mu$
- jets: anti-$k_T$ 0.4, $p_T > 25$ GeV, $|\eta| < 2.5$
- b tagging: 70% efficiency working point
Top Pair Modeling

- Simulations of top quarks + extra jets are still not supersophisticated
  - Leading order matched simulations (MadGraph/Sherpa) can certainly do a consistent job
  - NLO generation for extra heavy flavor just becoming available, not yet possible to do full (light+heavy quark) matched NLO with mass effects

- The vast majority of tt+bb in the relevant kinematic regions comes from parton shower, even in LO matched simulations
  - guessing the kinematic regions where ME and PS are important (which you need to do for Alpgen matching) is a bad idea

- We find best agreement in control regions with Powheg+Pythia (NLO) – this is our baseline
Pre-Fit Yields

- Most tt+light in l+jets 3b comes from $W \rightarrow cs$ tags
  - no analog in 2l
The Fit

• Systematic uncertainties are “profiled” in the fit: we provide an initial constraint and allow data to update the values & errors
  – in particular this constrains background systematics using bkg-rich regions, and allows in situ charm tagging measurement

• All control and signal regions for lepton + jets and dileptons fit simultaneously
  – of course we can cross check between the channels; excellent agreement seen on central value of systematic nuisance parameters
Top-Higgs coupling at ATLAS

**bb Systematics**

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<tr>
<th>Systematic uncertainty</th>
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<th>Comp.</th>
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Largest effects come from \(t\bar{t}+HF\) normalization, the \(t\bar{t}\) reweighting, and b-tagging.
Fit effect in Background-Rich Regions

**ATLAS** 
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

**Single lepton**
\( \geq 6 j, 2 b \)

**Pre-fit**

**Post-fit**

**Dilepton**
\( \geq 4 j, 2 b \)

**Pre-fit**

**Post-fit**
S/B Visualization

**ATLAS**

$t\bar{t}H (H \rightarrow b\bar{b})$

$\sqrt{s}=8$ TeV, $20.3$ fb$^{-1}$

Combined

Single lepton and Dilepton

**ATLAS**

allhad

$\sqrt{s}=8$ TeV

$20.3$ fb$^{-1}$
Combination, Couplings

\[ \mu_{\text{ttH}} < 3.2 \ (1.4 \text{ exp}) @ 95\% \text{ CL} \]

Signal significance: \( 2.5\sigma \ (1.5\sigma \text{ exp}) \)

**Sign flip for top coupling disfavored at 1\sigma by tree measurements alone (tH)**

**EPJ C 76, 6 (2016)**
Another reason to care about the top Yukawa: SM vacuum apparently metastable given $m_H$ and $m_t$ (aka, $y_t$). If actual $y_t$ is different from SM, this issue has a different resolution.

Buttazzo et al., arxiv:1307.3536
ttH in MSSM

- Scans of “pMSSM” models surviving experimental constraints
- Top coupling possibly strongly modified

Cahill-Rowley, Hewett, Ismail, Rizzo
arxiv:1308.0297