Higgs Yukawa Couplings
Latest results on the $H \rightarrow bb$ and $ttH/t\bar{H}$ channels

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May 2017, Shanghai Jiao Tong University, Shanghai (China)
• Coupling to fermions constrained by Run 1 measurements
  • Within the “Kappa framework”
• \( H \to \tau \tau \) already observed (J. Piedra Gomez talk)
• \( H \to b \bar{b} \) and \( ttH \) not yet observed
  • However indirect constraints are available (model dependent)

ATLAS+CMS Run 1

<table>
<thead>
<tr>
<th>Significance</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to \tau \tau )</td>
<td>5.0( \sigma )</td>
<td>5.5( \sigma )</td>
</tr>
<tr>
<td>( H \to b \bar{b} )</td>
<td>3.7( \sigma )</td>
<td>2.6( \sigma )</td>
</tr>
<tr>
<td>( ttH )</td>
<td>2.0( \sigma )</td>
<td>4.4( \sigma )</td>
</tr>
</tbody>
</table>

\[ \kappa_i^2 = \frac{\Gamma_i}{\Gamma_{SM}} \]

\( \kappa_\tau \)  
No BSM: \( \mathcal{O}(15\%) \)  
BSM in loops: \( \mathcal{O}(15\%) \)

\( \kappa_b \)  
No BSM: \( \mathcal{O}(25\%) \)  
BSM in loops: \( \mathcal{O}(20–30\%) \)

\( \kappa_\ell \)  
No BSM: \( \mathcal{O}(15\%) \)  
BSM in loops: \( \mathcal{O}(30\%) \)
**ttH channel**

- Direct way to probe the top Yukawa coupling
  - Complementary to loop-induced sensitivity in $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$

- Small production cross section and complex final state
  - Exploit various final states
  - Extensive use of MVA techniques

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Increase $\sigma \times \text{BR}$

Increase purity
**ttH(bb) Strategy**

- **Similar ATLAS and CMS analyses**
  - Basic `ttbar` selection *(One or two leptons)*
  - Then require additional jets (b-jets)

- **Split according to the number of (b)jets**
  - Exploit regions with different background composition
  - Low signal purity (Max: 3%-6%)

- **Advanced MVA techniques in signal enriched regions**
  - Signal depleted regions to control backgrounds

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**Dilepton Regions in Backup**

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ttH(bb) MVAs

- **ATLAS: 2 BDTs**
  - Reconstruction BDT to find “correct” jets assignment
  - Classification BDT to separate signal and backgrounds
    - Includes reconstruction variables

- **CMS: BDT and MEM**
  - Classification BDT to further split events into two regions
  - MEM discriminant in the fit
Both ATLAS and CMS increased analysis sensitivity with respect to run 1

However both analyses do not reach the $2\sigma$ level with $\sim 13\, fb^{-1}$
- Dominated by systematic uncertainties

Main challenge: control of $tt+bb$ background

But improvements are on the way
ttH (H→WW*, ZZ*, ττ)

- Split according to the number of leptons (e, μ) and τh in the final state
- ATLAS: Counting experiment in 6 categories
- CMS: Split further and make extensive use of MVAs techniques
- Excluding final state compatible with H→4l (dedicated analysis)

CMS categories

\[
\begin{array}{c|c|c|c|c}
\mu^±\mu^± & \mu^±e^± & e^±e^± & 3\ell & 4\ell \\
\hline
b\, tight & b\, tight & b\, loose & b\, tight & b\, loose \\
\end{array}
\]

1\ell 2\tau_h

\[
\begin{array}{c|c}
\ell^±\ell^±\tau_h & 3\ell 1\tau_h \\
\hline
Jet candidates from W decay & No jet candidates from W decay \\
\end{array}
\]

CMS PAS HIG-17-004

ATLAS-PAS HIG-17-003
**ttH 2ℓss MVAs (example)**

- Partial event “reconstruction” using BDTs
  - Identify jets from hadronic top decay and Higgs decay
- Train 2 kinematic BDTs: ttH vs ttbar and ttH vs ttV
- Map 2D into 1D (add bins with similar S/B)

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**2ℓss, ttH vs ttbar:** Includes hadronic top tagger

**2ℓss, ttH vs ttW/Z:** Include tagging of jets from Higgs
ttH Multilepton Results

- 3σ evidence reached with CMS multi-lepton analysis
  - Using 35.9 fb⁻¹
- Main challenge: control backgrounds from lepton and τₜₜ misidentification
  - Also control ttV backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS (13.2fb⁻¹)</strong></td>
<td>1.5σ</td>
<td>2.2σ</td>
</tr>
<tr>
<td><em><em>CMS</em> (35.9 fb⁻¹)</em>*</td>
<td>2.5σ</td>
<td>3.3σ</td>
</tr>
</tbody>
</table>

*w/o τₜₜ channels

σₜₜ dominated by systematic uncertainties
**ttH (H→γγ, 4l)**

- Ultra pure channels with very low yields
  - Dominated by the statistical uncertainties for now
- Exploit narrow resonance on top of continuum background

<table>
<thead>
<tr>
<th></th>
<th>Signal strength relative to SM prediction ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ttH (H→γγ)</strong></td>
<td>ATLAS (13.3 fb$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td>CONF-2016-068</td>
</tr>
<tr>
<td></td>
<td>$-0.3^{+1.2}_{-1.0}$</td>
</tr>
<tr>
<td><strong>ttH (H→4l)</strong></td>
<td>CMS (12.9 fb$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td>PAS HIG-16-020</td>
</tr>
<tr>
<td></td>
<td>$1.9^{+1.5}_{-1.2}$</td>
</tr>
<tr>
<td><strong>ttH (H→4l)</strong></td>
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<tr>
<td></td>
<td>PAS HIG-16-041</td>
</tr>
<tr>
<td></td>
<td>$0.0^{+1.2}_{-0.0}$</td>
</tr>
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</table>

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**ATLAS-CONF-2016-067**

- Data
- Background Fit
- Signal + Background Fit
- SM Signal + Background

**CMS PAS HIG-16-020**

- $\tau_s = 13$ TeV, 13.3 fb$^{-1}$
- $H\rightarrow\gamma\gamma$, $m_H = 125.09$ GeV

**CMS PAS HIG-16-041**

- $35.9$ fb$^{-1}$ (13 TeV)
- ttH hadronic

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2017-05-15
tbHj and tWHb

Destructive interference in SM

Significant cross section increase in Inverted Top Coupling scenario (ITC) $\kappa_t = -\kappa_v = -1$

**H→bb**

*Lepton + (b)jets final state*

*Two sub-samples: 3 or 4 b-tags*

*BDTs to find best jet assignment*
  *Two assumptions: tbHj or ttbar*

*Final classification BDT*
  *Exploits reconstructed properties*

**H→WW*, ZZ*, ττ**

*Multi-lepton + (b)jets final state*

*3 sub-samples: $\mu^+\mu^+, \mu^+e^+, 3\ell$*

*2 BDTs to discriminate tbHj vs ttV or ttbar*
  *Mapped to 1D Discriminant*

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tbHj and tWHb (Results)

- Run 1 sensitivity exceeded
- SM analysis clearly limited by statistical uncertainties
  - But powerful for some BSM scenarios

Limit on cross section @95% C.L. ($\kappa_V = 1.0$)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\kappa_t$</th>
<th>$\sigma^{SM}_{tH}$</th>
<th>$\sigma^{ITC}_{tH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tH(H\rightarrow bb)$</td>
<td>+1.0</td>
<td>$113.7 \times \sigma^{SM}_{tH}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−1.0</td>
<td>$6.0 \times \sigma^{ITC}_{tH}$</td>
<td></td>
</tr>
<tr>
<td>$tH+ttH(H\rightarrow ZZ,WW,\tau\tau)$</td>
<td>+1.0</td>
<td>$3.1 \times \sigma^{SM}_{tH+ttH}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−1.0</td>
<td>$1.4 \times \sigma^{ITC}_{tH+ttH}$</td>
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Limit as function of $\kappa_t$ ($\kappa_V = 1.0$)

Limit as function of $\kappa_t/\kappa_V$

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**H → bb**

- Despite having the largest BR, H → bb is not yet observed
  - 2.6σ LHC Run 1, 3.3σ Tevatron

- Associated or VBF production to suppress overwhelming multi-jet production (trigger)

- 3 analyses in run 2
  - Almost the same diagram
  - Different trigger strategy and final state

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**VH (H → bb)**
ATLAS-CONF-2016-091

**VBF (H → bb)**
CMS-PAS-HIG-16-003

**VBF,γ (H → bb)**
ATLAS-CONF-2016-063
- Split into categories depending on $N_{lep}$ and $N_{jets}$
- Require exactly 2 b-tags
- Cut on vector boson candidate $p_T$ to reduce multi-jet contribution

<table>
<thead>
<tr>
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<th>0 lepton</th>
<th>1 lepton</th>
<th>2 leptons</th>
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<tr>
<td>2 jets</td>
<td>$p_T &gt; 150\text{GeV}$</td>
<td>$p_T &gt; 150\text{GeV}$</td>
<td>$p_T &lt; 150\text{GeV}$</td>
</tr>
<tr>
<td>3 jets</td>
<td>$p_T &gt; 150\text{GeV}$</td>
<td>$p_T &gt; 150\text{GeV}$</td>
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Main bkg

- $Z+bb$, $W+bb$, $ttbar$
**VH, H → bb**

- Split into categories depending on $N_{\text{lep}}$ and $N_{\text{jets}}$
- Require exactly 2 b-tags
- Cut on vector boson candidate $p_T$ to reduce multi-jet contribution

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<tr>
<td>3 jets</td>
<td>$p_T^V &gt; 150 \text{GeV}$</td>
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Fit BDTs in all categories

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Run 1 sensitivity not yet reached with 13.2 fb\(^{-1}\)
- Similar contribution from statistical and systematic uncertainties
- Main challenge: control V+bb and ttbar backgrounds
  - Also control b-tagging related systematics

### ATLAS (13.2 fb\(^{-1}\))

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<th>Significance</th>
<th>Expected</th>
<th>Observed</th>
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<tr>
<td>ATLAS</td>
<td>1.94(\sigma)</td>
<td>0.42(\sigma)</td>
</tr>
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</table>

Run 1 ATLAS expected significance: 2.6\(\sigma\)
Similar strategies for ATLAS and CMS
- Main difference at trigger level

BDT with minimal correlation to the Higgs mass
- Categorize events in BDT bins
- Fit m(bb) in each category

Improve b-jet energy resolution
- Correct for semi-leptonic decays
- CMS: regression technique using a BDT and FSR correction

CMS Analysis
VBF topological trigger
Larger cross section but lower purity

ATLAS Analysis
Photon + VBF
topological trigger
Smaller cross section but higher purity

Categorization BDT
VBF, $H \rightarrow bb$ Results

- Search for resonant $H \rightarrow bb$ on top of non-resonant background

- Challenges
  - Improve $m(bb)$ resolution
  - Control non-resonant background

<table>
<thead>
<tr>
<th>Source</th>
<th>CMS 13TeV ($2.3 fb^{-1}$) PAS HIG-16-003</th>
<th>$-3.7^{+2.4}_{-2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF ($H \rightarrow bb$)</td>
<td>+ CMS 8TeV ($19.8 fb^{-1}$) PAS HIG-16-003</td>
<td>$1.3^{+1.2}_{-1.1}$</td>
</tr>
<tr>
<td>VBF, $\gamma$ ($H \rightarrow bb$)</td>
<td>ATLAS 13TeV ($12.6 fb^{-1}$) CONF-2016-063</td>
<td>$-3.9^{+2.8}_{-2.7}$</td>
</tr>
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</table>
Conclusion

- Coupling to $\tau$ leptons established in run 1
- Coupling to quarks still to be established
- No deviations from SM are observed

- $ttH$ run 2 analyses exceed run 1 sensitivity
  - CMS: Evidence from $ttH$(multi-lepton) with full 2015+2016 data
- Not sensitive yet to $H\rightarrow bb$

- Many analyses still updating to the full available dataset
  - Complex analyses with continuous improvements
  - Expect updates in the near future

- More details tomorrow (Higgs session)
  - C. C. Campana’s and Z. Liang’s talks
Backup
Dilepton regions
**Background composition for the different regions**

**ATLAS**

*Simulation Preliminary*

- $t\bar{t} + \text{light}$
- $t\bar{t} + \geq 1c$
- $t\bar{t} + \geq 1b$
- $t\bar{t} + V$
- Non-$t\bar{t}$

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**Background composition for the different regions**

**ATLAS**

*Simulation Preliminary*

- $t\bar{t} + \text{light}$
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- $t\bar{t} + V$
- Non-$t\bar{t}$

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2017-05-15
ttH 3ℓ BDT discriminant

- Evaluate MEM weights under ttH, ttW, ttZ hypotheses
  - Build likelihood ratio of ttV vs ttH+ttV
- MEM weight included in ttH vs ttV BDT
- Another BDT to discriminate ttH and ttbar
- Mix both BDTs
  - Adding bins with similar S/B

\[-\log \left( \frac{\sigma_{ttZ}w_{ttH} + k \cdot \sigma_{ttW}w_{ttW}}{\sigma_{ttH}w_{ttH} + \sigma_{ttZ}w_{ttZ} + k \cdot \sigma_{ttW}w_{ttW}} \right)\]
ttH, $H \rightarrow \tau\tau$ discriminants

- Split into 3 channels with leptons and $\tau_h$ in the final state
  - Following similar techniques as ttH with leptons and muons
- $2\ell ss + 1\tau_h$
  - MEM likelihood ratio with ttH vs ttZ and ttbar hypotheses
  - Further split according to the presence of two jets compatible with a W boson decay
- $1\ell + 2\tau_h$
  - BDT trained against ttbar
- $3\ell + 1\tau_h$
  - 2 BDTs: against ttV and ttbar
  - 1D bin mapping according to S/B ($D_{MVA}$)
Prefit vs postfit

- **ttH(bb) ATLAS**
- **tt+b and tt+c normalization systematics not included in pre-fit plot**
  - Free parameters of the fit
Prefit vs postfit

- $ttH(bb)$ CMS
- Postfit reduction of systematics
  - Mostly on normalization systematics
tbHj and tWHb, H→bb

- Analysis performed in the lepton + (b)jets final state
- Split into two sub-samples: 3 b-tags and 4 b-tags
- BDTs to find best jet assignment and reconstruct the event
  - Under two assumptions: tbHj and ttbar
- Final classification BDT that exploits reconstructed properties

Destructive interference in SM

Significant cross section increase in inverted top coupling scenario

\[ \kappa_t = -\kappa_v = -1 \]
Comparable sensitivity to Run 1 analysis
  - With only 2.3 fb\(^{-1}\)

SM analysis clearly limited by statistical uncertainties
  - But powerful for some BSM scenarios

Final BDT output

Limit on cross section @95% C.L.

<table>
<thead>
<tr>
<th>(\kappa_t)</th>
<th>(\kappa_v)</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.0, 1.0</td>
<td>+1.0</td>
<td>113.7</td>
</tr>
<tr>
<td>-1.0, 1.0</td>
<td>+1.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Limit as function of \(\kappa_t\)

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