Higgs boson production via ttH

ATLAS and CMS results

Judith Katzy on behalf of the ATLAS and CMS collaborations
Motivation

**top-Higgs coupling largest in SM**

\[ y_t \sim \frac{m_t}{v} \]

- **Motivation**
  - \( \sigma_{ttH} \sim |y_t|^2 \)
  - \( \sigma_{tH} \sim |y_t|^2 \)

**Motivation**

**ttH+tH: direct probe of top-Higgs coupling**

**Motivation**

**ttH+tH: direct probe of top-Higgs coupling**

**Motivation**

**ttH+tH: direct probe of top-Higgs coupling**
**Motivation**

Sign of $y_t$ & CP structure of fermionic Higgs couplings

$t$-channel $tHq$ production

SM: $y_t \sim 1$, destructive interference: $\sigma_{tH} \sim 74$ pb

BSM: $y_t \sim -1$, constructive interference $\sigma_{tH} \sim 850$ pb

**tH sensitive to sign of $y_t$**

CP properties talk by Ahmed
Motivation
Unique opportunities to probe Effective Field Theory

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \]

Study dimension six operators affecting \(ttH\) and \(tH\) production

Probe Wilson coefficients in \(ttH\) production as a function of Higgs \(p_T\)

Use STXS bins in Higgs \(p_T\)
Motivation
Unique opportunities to probe Effective Field Theory

**ATLAS Simulation** $\sqrt{s}=13$ TeV $139fb^{-1}$ $H \rightarrow \gamma\gamma$, $m_H = 125.09$ GeV, $\Lambda = 1$ TeV

<table>
<thead>
<tr>
<th>Operator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuG</td>
<td>0.1</td>
</tr>
<tr>
<td>CuH</td>
<td>1.0</td>
</tr>
<tr>
<td>CG</td>
<td>1.0</td>
</tr>
<tr>
<td>Cqq(3)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Higgs pT bins

Unique sensitivity to some operators
Measurements

Rare process in different Higgs decay modes

\[ N_{\text{events}} = L \cdot \sigma_{ttH} \cdot B(H) \cdot B(\text{ttbar}) \cdot \varepsilon \cdot \Lambda \]

\[ \sigma_{ttH} \sim 530 \text{ fb} \]
\[ \sigma_{tH} \sim 74 \text{ fb} \]

<table>
<thead>
<tr>
<th>Higgs decay mode</th>
<th>B. ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-&gt;bb</td>
<td>58.1 %</td>
</tr>
<tr>
<td>H-&gt;WW</td>
<td>21.5 %</td>
</tr>
<tr>
<td>H-&gt;\tau\tau</td>
<td>6.3 %</td>
</tr>
<tr>
<td>H-&gt;ZZ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-&gt; qq, ll</td>
</tr>
<tr>
<td>H-&gt;\gamma\gamma</td>
<td>0.23 %</td>
</tr>
<tr>
<td>H-&gt;ZZ</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-&gt;4 leptons (e,\mu)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ttbar decay mode</th>
<th>B. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Di-lepton (e,\mu)</td>
<td>4%</td>
</tr>
<tr>
<td>Single lepton (e,\mu) + jets</td>
<td>30%</td>
</tr>
<tr>
<td>All jets</td>
<td>44%</td>
</tr>
</tbody>
</table>

"ML"
# Measurements

## ATLAS and CMS ttH and tH measurements at 13 TeV

<table>
<thead>
<tr>
<th></th>
<th>H-&gt;bb</th>
<th>H-&gt;WW, ττ, ZZ</th>
<th>H-&gt;γγ</th>
<th>HZZ-&gt;4l</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full Run2</td>
<td>80 ifb</td>
<td>Full Run2</td>
<td>Full Run2</td>
</tr>
<tr>
<td></td>
<td>σ_{ttH}</td>
<td>σ_{ttH}</td>
<td>σ_{ttH}</td>
<td>σ_{ttH}</td>
</tr>
<tr>
<td></td>
<td>p_{T}(H)</td>
<td>Full Run2 0l H-&gt;τ_hadτ_had</td>
<td>p_{T}(H)</td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>36 ifb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>σ_{ttH}</td>
<td>Full Run2 σ_{ttH} σ_{tH}</td>
<td>Full Run2</td>
<td>Full Run2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full Run2 σ_{tH} p_{T}(H)</td>
<td>σ_{ttH}</td>
<td>σ_{ttH}</td>
</tr>
<tr>
<td></td>
<td>Full Run 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>boosted σ_{ttH}, p_{T}(H) &gt;200 GeV</td>
<td>Full Run2 p_{T}(H)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} \]
ttH H->bb

Measurement advantages and challenges

H->bb has largest branching ratio (58%)

Due to large combinatorics of 4 b-jets no Higgs mass peak

Use leptonic top decays to avoid QCD multi-jet background
- Fully hadronic top decays have been tried but yield poor resolution

Typically signal / background below 10% even in most sensitive signal regions

Large irreducible background ttbb
- Various codes of ttbb@NLO 4FS calculations matched to PS available and used by recent analyses in ATLAS and CMS for tt + ≥1b
- Different philosophy of estimating modelling uncertainties in ATLAS and CMS

See talk by Ana Cueto Gomez on background modelling
**ttH H→bb**

**ATLAS full Run-2 analysis 139 fb⁻¹**

**Strategy:** Measure in pure phase space to minimise problems with modelling of various tt+jets backgrounds:
- Require ≥ 1 lepton, light jets and 4 well identified b-jets in the signal region
- Measure in resolved and boosted channel

**Analysis chain:**
- Reconstructed Higgs candidate and split into $p_T^H$
- Separate signal vs background with MVA based on Higgs candidate and event properties
- Perform Maximum Likelihood fit to signal and control regions to extract $\mu_{ttH}$

---

**ATLAS**

<table>
<thead>
<tr>
<th>$\sqrt{s} = 13$ TeV, 139 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
</tr>
<tr>
<td>SR₆³⁰⁰</td>
</tr>
<tr>
<td>Post-Fit</td>
</tr>
</tbody>
</table>

* normalised to total Bkg.

---

**ATLAS**

<table>
<thead>
<tr>
<th>$\sqrt{s} = 13$ TeV, 139 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton</td>
</tr>
<tr>
<td>SR₁⁰⁰</td>
</tr>
<tr>
<td>Pre-Fit</td>
</tr>
</tbody>
</table>

* normalised to total Bkg.
Inclusive $\mu_{\text{ttH}}$ systematics limited; $\mu_{\text{ttH}}$ @ high Higgs pT stats limited

Dominant Uncertainty: Modelling of ttbb background
ttH H->bb, boosted Higgs

Probe $\mu_{\text{ttH}}$ at high $p_T$ and probe EFT

Single lepton+2 resolved b-jets, boosted object with $p_T>200$ GeV containing bb

Use ttbb@NLO 4FS as background MC for ttbb

Higgs $p_T$ bins [200,300][300,450][450,∞]

### Source of uncertainty

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta \mu_{ttZ}$</th>
<th>$\Delta \mu_{ttH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} + c\bar{c}$ cross section</td>
<td>+0.27</td>
<td>+0.14</td>
</tr>
<tr>
<td>$t\bar{t} + b\bar{b}$ cross section</td>
<td>+0.18</td>
<td>+0.16</td>
</tr>
<tr>
<td>$t\bar{t} + 2b$ cross section</td>
<td>+0.03</td>
<td>±0.09</td>
</tr>
<tr>
<td>$\mu_R$ and $\mu_F$ scales</td>
<td>+0.12</td>
<td>+0.11</td>
</tr>
<tr>
<td>Parton shower</td>
<td>+0.16</td>
<td>+0.07</td>
</tr>
<tr>
<td>$b$ tagging efficiency</td>
<td>+0.25</td>
<td>±0.10</td>
</tr>
<tr>
<td>$b\bar{b}$ tagging efficiency</td>
<td>-0.13</td>
<td>-0.13</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>±0.11</td>
<td>±0.11</td>
</tr>
<tr>
<td>Jet mass scale and resolution</td>
<td>±0.10</td>
<td>±0.08</td>
</tr>
</tbody>
</table>
ttH H->bb, boosted Higgs
Probe $\mu_{ttH}$ at high Higgs pT and Wilson Coefficients

Observed confidence intervals constrained by ttH
ttH + tH in ML
ATLAS + CMS

Various analysis channels depending on #leptons (e,µ) and relative sign, #hadronic τ

**ttH: 10 channels**
Most sensitive:
2l SS 0τ
3l 0τ
2l 2τ

**tH: 3 channels**
2ISS+0τ, 2ISS+1τ, 3l

**Key issues:**
Large irreducible ttW background
- Large uncertainties in NLO predictions
- Different philosophy of estimating modelling uncertainties in ATLAS and CMS
Leptonic backgrounds of various sources
**ttH+tH in ML**

**CMS full Run2 137 fb⁻¹**

S/B for ttH up to 35%  tH up to 3.3%

**Separate regions** for ttH, tH, ttW, other backgrounds, CR (ttZ,ZZ,WZ)

**Maximum likelihood Fit:**
Extract  ttH and tH  
and normalisation of ttW and ttZ

**Diagram:**
- 2lss + 0τ_{h}
- 3l + 0τ_{h}
- 2lss + 1τ_{h}
- 1l + 1τ_{h}

**Classifiers:**
- DNN
- BDT

**Channels:**
- + 6 channels

**Regions:**
- 3l – CR
- 4l – CR
**ttH+tH in ML**

**CMS full Run2 137 fb$^{-1}$ - ttH and tH cross section assuming SM kinematics**

- **Dominant systematic uncertainty:** normalisation of MC estimated processes
- **μ_{ttH}=0.92 ±0.19(stat)+0.17(syst) -0.13**

- **Dominant systematic uncertainty:** Misidentified leptons + flips
- **μ_{tH}= 5.7 ± 2.7(stat) ± 3.0(syst)**

- **μ_{ttW} ~ 1.5 μ_{SM}**
ttH+tH in ML

Extract $y_t$ without SM assumptions

Take interference effects in tHq on kinematic observables into account

extract $\kappa_t = y_t(\text{meas}) / y_t(\text{SM})$

\[-0.7 < \kappa_t < -0.9 \ \text{or} \ 0.7 < \kappa_t < 1.1 \ \text{at 95% CL}\]
ttH in ML

ATLAS preliminary 80 fb$^{-1}$

\[ \hat{\lambda}_{t\bar{t}W}^{2\ell} = 1.56^{+0.30}_{-0.28}, \quad \hat{\lambda}_{t\bar{t}W}^{2\ell}HJ = 1.26^{+0.19}_{-0.18}, \text{ and } \hat{\lambda}_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28} \]
**ttH H→γγ**

ATLAS+CMS full Run2: inclusive ttH + tH cross sections

**Talk by Pascal**
**ttH H→γγ**

**ATLAS and CMS differential in Higgs pT**

**Event yields in full Run 2**

<table>
<thead>
<tr>
<th>Analysis Category</th>
<th>ttH</th>
<th>tH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H pT&lt;60</strong></td>
<td>94</td>
<td>4</td>
</tr>
<tr>
<td><strong>H pT&gt;300</strong></td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td><strong>Truth</strong></td>
<td>93</td>
<td>2</td>
</tr>
<tr>
<td><strong>Reconstructed</strong></td>
<td>92</td>
<td>5</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>0.75</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>S/B</strong></td>
<td>1.32</td>
<td>0.39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis Category</th>
<th>tH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H pT&lt;60</strong></td>
<td>4</td>
</tr>
<tr>
<td><strong>H pT&gt;300</strong></td>
<td>16</td>
</tr>
<tr>
<td><strong>Truth</strong></td>
<td>15</td>
</tr>
<tr>
<td><strong>Reconstructed</strong></td>
<td>22</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>0.25</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>0.05</td>
</tr>
<tr>
<td><strong>S/B</strong></td>
<td>0.06</td>
</tr>
</tbody>
</table>

- $p_T^H < 60$ GeV, High-purity
- $p_T^H < 60$ GeV, Med-purity
- $60 \leq p_T^H < 120$ GeV, High-purity
- $60 \leq p_T^H < 120$ GeV, Med-purity
- $120 \leq p_T^H < 200$ GeV, High-purity
- $120 \leq p_T^H < 200$ GeV, Med-purity
- $200 \leq p_T^H < 300$ GeV
- $p_T^H \geq 300$ GeV
Measurements have very small systematic and large statistical uncertainties.
**ttH H->ZZ->4l**

ATLAS + CMS full Run2 data

![Graph 1](image1.png)

**Inclusive H->4µ**

- **Sigma ttH B**: measured in CMS and ATLAS.
  - CMS: $3^{+16}_{-3}$
  - ATLAS: $1.6 \pm 1.7^{+0.3}_{-0.2}$

![Graph 2](image2.png)

**ttH H->4l**

- **Data**
  - H(125)
  - qq→ZZ, Zγ*
  - gg→ZZ, Zγ*
  - EW
  - Z+X

- **Events**
  - CMS: $3^{+16}_{-3}$
  - ATLAS: $1.6 \pm 1.7^{+0.3}_{-0.2}$
Combined Results for each experiment

Combination of ttH results in different channels

<table>
<thead>
<tr>
<th>Higgs boson production via ttH and tH</th>
<th>Judith Katzy</th>
<th>Higgs2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH+tH, H-&gt;γγ, 4l, bb 139 fb⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH, H-&gt;WW,ZZ, ττ 36 fb⁻¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

H->γγ, 4l, ML 139 fb⁻¹
H->bb 36 fb⁻¹

statistical and systematic uncertainties of similar size

μ_{ttH} known at ~20%

σ_{tH} not yet observed
Measurements of ttH and tH performed on full Run2 data set in many channels, few are still in preparation

Measurements of ttH in differential Higgs pT are statistics limited in most of the phase space

Combination of Run2 results of ATLAS and CMS would be beneficial
- Need to overcome significant differences in treatment of systematic uncertainties in ttHML and ttHbb
- LHC Higgs WG note on theory uncertainty treatment in cds; to appear on arXiv soon

13.6 TeV: increase of ttH and tH cross section by 12%
Thank you
**ttH 0 lepton, H→τₜ hadτₜ had**

**ATLAS full Run2**

**ATLAS**

\[
H \rightarrow \tau\tau \quad \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1}
\]

- Total
- Stat.
- Theo.

\[|y_H| < 2.5\]

<table>
<thead>
<tr>
<th>Process</th>
<th>((\sigma \times B)^{\text{meas}} / (\sigma \times B)^{\text{SM}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-tt(0L)H(\tau_h \tau_h))</td>
<td>1.02 (Stat., Syst.) ( +0.97^{-0.81} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>(V(\text{had})H)</td>
<td>0.82 (+0.37\text{-}0.33) (Stat., Syst.)</td>
</tr>
<tr>
<td>Boost</td>
<td>0.99 (+0.26\text{-}0.21) (Stat., Syst.)</td>
</tr>
<tr>
<td>VBF</td>
<td>0.82 (+0.17\text{-}0.14) (Stat., Syst.)</td>
</tr>
<tr>
<td>Comb.</td>
<td>0.93 (+0.13\text{-}0.12) (Stat., Syst.)</td>
</tr>
</tbody>
</table>
**ttH H→bb**

**CMS 36 fb⁻¹**

- **>= 1 leptonic top decay**

- Measurement performed in phase space starting with 3b

- Use of MVA techniques to separate signal from background and different background categories

- Use **tt@NLO 5FS** as background MC also for ttbb

- **Systematic limited**

- Dominant uncertainty:
  - uncertainty on tt+heavy flavour rate

**Best fit \( \mu = \sigma/\sigma_{SM} \) at \( m_H = 125 \text{ GeV} \)**
STXS binning $ttH + tH$

Including Higgs $p_T$

$t\bar{t}H$

$[ \, pp \to ttH \, ]$

$p_T^H \, < \, 60 \, \text{GeV}$

$60 \, \leq \, p_T^H \, < \, 120 \, \text{GeV}$

$120 \, \leq \, p_T^H \, < \, 200 \, \text{GeV}$

$200 \, \leq \, p_T^H \, < \, 300 \, \text{GeV}$

$300 \, \leq \, p_T^H \, < \, 450 \, \text{GeV}$

$p_T^H \, \geq \, 450 \, \text{GeV}$

$tH$

$[ \, pp \to tH + X \, ]$
ttHbb SR background composition
ATLAS full Run2

- dilepton

ATLAS

- \( \sqrt{s} = 13\text{ TeV} \)
- Dilepton
- \( \text{SR}^{\text{lep}} \)
- \( p_T^l \in [0,120) \text{ GeV} \)
- \( \text{SR}^{\text{lep}}_{120} \)
- \( p_T^l \in [120,200) \text{ GeV} \)
- \( \text{SR}^{\text{lep}}_{200} \)
- \( p_T^l \in [200,300) \text{ GeV} \)
- \( \text{SR}^{\text{lep}}_{300} \)
- \( p_T^l \in [300,\infty) \text{ GeV} \)

- l+jets

ATLAS

- \( \sqrt{s} = 13\text{ TeV} \)
- Single lepton
- \( \text{SR}^{\text{l+j}} \)
- \( p_T^l \in [0,120) \text{ GeV} \)
- \( \text{SR}^{\text{l+j}}_{120} \)
- \( p_T^l \in [120,200) \text{ GeV} \)
- \( \text{SR}^{\text{l+j}}_{200} \)
- \( p_T^l \in [200,300) \text{ GeV} \)
- \( \text{SR}^{\text{l+j}}_{300} \)
- \( p_T^l \in [300,\infty) \text{ GeV} \)

- Boosted

ATLAS

- \( \sqrt{s} = 13\text{ TeV} \)
- \( \text{SR}^{\text{b+boosted}} \)
- \( p_T^b \in [0,120) \text{ GeV} \)
- \( \text{SR}^{\text{b+boosted}}_{120} \)
- \( p_T^b \in [120,200) \text{ GeV} \)
- \( \text{SR}^{\text{b+boosted}}_{200} \)
- \( p_T^b \in [200,300) \text{ GeV} \)
- \( \text{SR}^{\text{b+boosted}}_{300} \)
- \( p_T^b \in [300,\infty) \text{ GeV} \)

CR_{lep to}
**ttH H->bb**

ATLAS full Run-2 analysis 139 fb⁻¹
ttHML

CMS full Run2 139 ifb

- ttW ~1.5 times higher in data

- $\zeta_t = \frac{y_t(\text{meas})}{y_t(\text{SM})}$

- $-0.7 < \zeta_t < -0.9$ or $0.7 < \zeta_t < 1.1$ at 95% CL
ttHbb

ATLAS 139 fb⁻¹
ttW Measurements

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>$\mu_{tZ}$</th>
<th>$\mu_{ttW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>1.08 ± 0.14</td>
<td>1.44 ± 0.32</td>
</tr>
<tr>
<td>2$\ell$-OS</td>
<td>0.73 ± 0.28</td>
<td>-</td>
</tr>
<tr>
<td>3$\ell$ tZ</td>
<td>1.08 ± 0.18</td>
<td>-</td>
</tr>
<tr>
<td>2$\ell$-SS and 3$\ell$ ttW</td>
<td>-</td>
<td>1.41 ± 0.33</td>
</tr>
<tr>
<td>4$\ell$</td>
<td>1.21 ± 0.29</td>
<td>-</td>
</tr>
</tbody>
</table>

CMS: arXiv:2208.0648

138 fb$^{-1}$ (13 TeV)

CMS Measurements

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

Nominal ± stat ± syst
ee: 845 ± 117 ± 111
$\ell\mu$: 996 ± 61 ± 68
$\mu\mu$: 868 ± 63 ± 64
Dilepton: 905 ± 42 ± 51
Trilepton: 649 ± 104 ± 96
Combined: 868 ± 40 ± 51
ttH+tH in ML

Example: nodes of 2ISS+0τ

- ttW  
- Misidentified leptons  
- ttH  
- tH
**ttH H→ZZ→4l**

ATLAS + CMS full Run2 data
Combinations
Differential in Higgs $p_T$

**ATLAS**

$\sqrt{s} = 13$ TeV, $36.1 - 139$ fb$^{-1}$

$m_H = 125.09$ GeV, $|\eta_H| < 2.5$

$P_{SM} = 65\%$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF+bbH$</td>
<td>1.03</td>
<td>±0.07 (±0.04, ±0.06)</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>1.10</td>
<td>±0.12 (±0.08, ±0.09)</td>
<td></td>
</tr>
<tr>
<td>WH</td>
<td>1.16</td>
<td>±0.22 (±0.17, ±0.15)</td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>0.96</td>
<td>±0.21 (±0.16, ±0.13)</td>
<td></td>
</tr>
<tr>
<td>$ttH$</td>
<td>0.74</td>
<td>±0.24 (±0.17, ±0.16)</td>
<td></td>
</tr>
<tr>
<td>$tH$</td>
<td>6.6</td>
<td>±3.8 (±3.3, ±2.6)</td>
<td></td>
</tr>
</tbody>
</table>

Cross-section normalized to SM value