Associated production of top quarks with the Higgs boson

Precision2016, Quy Nhon (Viet Nam) - 29/09/2016

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Outline

**ttH production**: direct probe of top Yukawa coupling

**tHq production**: probing the sign of top Yukawa coupling

**Flavour changing neutral current (FCNC) tH coupling**
**ttH production at 13 TeV**

**Summary of Run I**

**Higgs couplings**

**LHC 8 TeV:** observation at $4.4\sigma$ (2.0$\sigma$ expected)

- **Indirect (loop level) probe of top Yukawa coupling**
- **Direct (tree level) probe of top Yukawa coupling**

**H (N3LO QCD + NLO EW)**

- **$p\bar{p} \rightarrow H (N3LO QCD + NLO EW)$**
- **$p\bar{p} \rightarrow g\bar{g}H (NNLO QCD + NLO EW)$**
- **$p\bar{p} \rightarrow WH (NNLO QCD + NLO EW)$**
- **$p\bar{p} \rightarrow ZH (NNLO QCD + NLO EW)$**
- **$p\bar{p} \rightarrow b\bar{b}H (NNLO QCD in 5FS, NLO QCD in 4FS)$**
- **$p\bar{p} \rightarrow t\bar{t}H (NLO QCD, t-ch + s-ch)$**

**Direct (tree level) probe of top Yukawa coupling**

- **$p\bar{p} \rightarrow b\bar{b}H (NNLO QCD in 5FS, NLO QCD in 4FS)$**
- **$p\bar{p} \rightarrow t\bar{t}H (NLO QCD, t-ch + s-ch)$**

- **ttH**
  - ~1% of total Higgs boson cross section
  - Large increase of **ttH cross section from 8 TeV to 13 TeV:** x3.8 (ttbar x3.3, ttZ x3.7, ttW x2.4)
Searches for ttH production

**ttH, H→bb:** 58.1%
- High cross section x BR, but multi-jet background
- ATLAS : 2015 + 2016 data
- CMS : 2015 data

**ttH, H→γγ:** 0.23%
- Clean signature thanks to excellent mass resolution, but small branching ratio
- ATLAS : 2015 + 2016 data
- CMS : 2015, 2016 data

**ttH multilepton : H→WW (21.5%), H→ZZ (2.6%) and H→ττ (6.3%)**
- H→WW, H→ZZ semi-leptonic and leptonic decays
- Lower rate than H→bb, low background final state
- ATLAS : 2015 + 2016 data
- CMS : 2015 + 2016 data
Signal region targeting lepton+jets and dileptons

- **l+jets**: $\geq 1$ lepton, $\geq 4$ jets, $\geq 3$ b-tag
- **2l**: 2 opposite sign lepton, $\geq 3$ jets, $\geq 3$ b-tag
- Categorize events in number of jets and b-jets

- **$\text{ttbar} + \geq 1\text{b}$**: major background in signal regions
- **HT** distribution used to normalise backgrounds in control regions
**ATLAS ttH, H → bb**

**ATLAS-CONF-2016-080**

**Analysis strategy: two-step multivariate technique**

- **Reconstruction BDT**: Match reconstructed jets to Higgs and top quark jets
- **NN/BDT output**: includes previous BDT + kinematic variables
- All regions included in final likelihood fit

Theory uncertainties on ttbar + ≥1b is Δμ~0.5, already dominates the measurement.
Analysis targeting lepton+jets and dileptons

- **l+jets**: ≥ 1 lepton, ≥ 4 jets, ≥ 3 b-tag (4j 2b not in the fit)
  - Includes **boosted jets** for the first time (fat jet substructure)
- **2l**: 2 opposite sign lepton, ≥ 3 jets, ≥ 2 b-tag

**CMS Simulation - dilepton**

- 3 jets, 2 b-tags
- 3 jets, 3 b-tags
- ≥ 4 jets, ≥ 4 b-tags

**CMS Simulation - lepton+jets**

- > 6 jets, 2 b-tags
- 4 jets, 3 b-tags
- 5 jets, 3 b-tags

Mass resolution ~10%, jet combinatorics: use **multivariate methods** in jet/b-jet categories

- **BDT**
- **Matrix Element Method (MEM)**
More data is needed for an observation at ATLAS or CMS.
Targeting 2 lepton same-sign (2lss) and ≥3 leptons (3l)
- 2 same sign leptons: ≥4 jets, ≥1 b-tag
- 3 leptons: ≥2 jets, ≥1 b-tag
- Backgrounds: tt+W/Z, tt+jets (same-sign required to reduce Drell-Yan and ttZ)
- Background normalisation from control region: loosened identification (fakes), Z→ll (mis-charge = “flips”, 2lss only)

Analysis categories:
- Lepton identification with a BDT using shape, isolation and overlapping jet information
**Analysis sensitivity:**
- Train 2 BDTs, against ttbar and ttW/Z
- 3l category: include MEM as BDT input (new)
- Main syst. uncert.: tight lepton selection and fakes
ATLAS $ttH$ multilepton

ATLAS analysis: 4 channels

- $2\ell$ same sign ($ee, e\mu, \mu\mu$), no $\tau$ had: $\geq 5$ jets, $\geq 1$ b-tag
- $2\ell$ same sign, $1$ $\tau$ had: $\geq 4$ jets, $\geq 1$ b-tag
- $3\ell$: $\geq 4$ jets, $\geq 1$ b-tag; or $\geq 3$ jets, $\geq 2$ b-tag
- $4\ell$: $\geq 2$ jets, $\geq 1$ b-tag

- Similar method to CMS for background measurement
- Fake $\tau$ from simulation, normalised to control region
- Main systematic uncertainties: Fakes and flips $\Delta \mu \sim 0.6$

Cut and count analysis in 6 categories

![Cut and count analysis graph]

![Simulation Preliminary]

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

<table>
<thead>
<tr>
<th>$2\ell$ $0\tau_{\text{had}}$</th>
<th>$2\ell$ $1\tau_{\text{had}}$</th>
<th>$3\ell$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.0 \pm 2.1$</td>
<td>$6.2 \pm 3.6$</td>
<td>$0.5 \pm 1.7$</td>
<td>$&lt; 2.2$ (68% CL)</td>
</tr>
<tr>
<td>$(1.2, +1.7)$</td>
<td>$(+2.8, +2.3)$</td>
<td>$(+1.2, +1.2)$</td>
<td></td>
</tr>
<tr>
<td>$(-1.1, -1.3)$</td>
<td>$(-2.3, -1.4)$</td>
<td>$(-1.0, -1.3)$</td>
<td></td>
</tr>
</tbody>
</table>

Combination $\mu_{ttH}$ for $m_{ttH} = 125$ GeV: $2.5 \pm 1.3$ (stat., syst.)
- Look for **small signal peak (BR~0.2%) over large background**

- **Photon energy resolution** ~1% depending on categories: calibration is crucial

- **Photon identification**: reject jets faking photons with shower shape and isolation: BDT (CMS), cut-based (ATLAS)
2 ttH categories: hadronic and leptonic

- Tighten photon pT/m requirement relative to inclusive categories (targeting ggh production)
- Control region with inverted photonId is used to predict expected background for optimisation

**ttH hadronic** tag: 0 lepton, ≥5 jets, ≥1 b-tag

**ttH leptonic** tag: ≥1 lepton, ≥2 jets, ≥1 b-tag

- ttH hadronic/leptonic combined: $\mu = 1.9^{+1.5}_{-1.2}$ measured simultaneously with other production mechanisms
- Measurement is dominated by statistical uncertainties
2 ttH categories: hadronic and leptonic
- Control region with inverted photonId
- ttH hadronic/leptonic combined: $\mu = -0.25^{+1.26}_{-0.99}$ measured simultaneously with other production mechanisms (ratio WH/ZH assumed as SM)
- Measurement is dominated by statistical uncertainties

**ttH hadronic** tag: 0
lepton, $\geq 5$ jets, $\geq 1$ b-tag

**ttH leptonic** tag: $\geq 1$
lepton, $\geq 2$ jets, $\geq 1$ b-tag
**ttH summary and projections**

**CMS**
- $ttH$, $H\rightarrow bb$ (2015): $\mu=2.0^{+1.8}_{-1.8}$
- $ttH$ multilepton (2015+2016): $\mu=2.0^{+0.8}_{-0.7}$
- $ttH$, $H\rightarrow \gamma\gamma$ (2016): $\mu=1.9^{+1.5}_{-1.2}$

**Projections at HL-LHC $L=3000$ fb$^{-1}$**

**CMS expected precision on top - Higgs coupling (%)**

<table>
<thead>
<tr>
<th>$L$ (fb$^{-1}$)</th>
<th>$\kappa_T$</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_T$</th>
<th>$\kappa_T$</th>
<th>$\kappa_T$</th>
<th>$\kappa_{ZT}$</th>
<th>$\kappa_{ttH}$</th>
<th>$\text{BR}_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>[5, 7]</td>
<td>[4, 6]</td>
<td>[4, 6]</td>
<td>[6, 8]</td>
<td>[10, 13]</td>
<td>[6, 8]</td>
<td>[41, 41]</td>
<td>[23, 23]</td>
<td>[14, 18]</td>
</tr>
<tr>
<td>3000</td>
<td>[2, 5]</td>
<td>[2, 5]</td>
<td>[2, 4]</td>
<td>[3, 5]</td>
<td>[4, 7]</td>
<td>[7, 10]</td>
<td>[2, 5]</td>
<td>[10, 12]</td>
<td>[8, 8]</td>
</tr>
</tbody>
</table>

**ATLAS**

**Expected precision on $ttH$ signal strength (%)**

<table>
<thead>
<tr>
<th>$\mu \propto K_t$</th>
<th>$\Delta \hat{\mu}/\hat{\mu}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$</td>
<td>$+21$</td>
</tr>
</tbody>
</table>

**CMS-NOTE-13-002**
- Extrapolated from 8 TeV first measurements, same syst.
- $\Delta K_t$: from $H\rightarrow \gamma\gamma$ and $H\rightarrow bb$: 10% (7% if half theory uncert.)

**ATLAS PHYS-PUB-2014-012**
- $ttH, H\rightarrow \gamma\gamma$ 1l,2l only, same extrapolation
- Similar experimental sensitivity

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**Parameter value**

Run I: $\mu=2.3^{+0.7}_{-0.6}$
tHq production and negative coupling

\( H \rightarrow \gamma \gamma \) sensitive to the sign of top-Higgs coupling

\[ \Gamma(H \rightarrow \gamma \gamma) \propto \left| \kappa F A_t + \kappa V A_W \right|^2 \]

On top of ttH production, can search for tHq production to lift the degeneracy
- Destructive interference between coupling to top and W: tHq has a 30 smaller cross section than ttH predicted in the SM

Signature: tH + forward jet

Negative top-Higgs coupling
- can increase a lot (~x15) the tHq cross section
- and induce BR(H\rightarrow\gamma\gamma) ~x2

\[ \kappa F^{1-2} \]

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CMS tHq 8 analyses carried out in same final states as ttH:

- \(H \rightarrow \gamma\gamma\): background fit in leptonic channels, also done at ATLAS
- \(H \rightarrow bb\): Use NN as discriminant in 3b/4b, e/\(\mu\) categories
- Multilepton: Bayes classifier in 3l, e\(\mu\), \(\mu\mu\) categories
- \(H \rightarrow \tau\tau\): Fisher discriminant in e\(\mu\)\(\tau\), \(\mu\mu\)\(\tau\) categories

**CMS Combination**: Exclude \(\sigma < 2.8 \times \sigma_{K_t=-1}\) (observed limit)

**ATLAS**: \(K_t \in [-1.3, 8.0]\)
tHq, H→bb at 13 TeV

**CMS HIG-16-019**

Analysis performed with 2015 data:
- **Jet assignment** with a reconstruction BDT under tHq and ttbar hypotheses
- Signal / background discrimination with a classification BDT

=> Done for each benchmark point in the $\kappa_t$ / $\kappa_V$ plane

- Similar sensitivity to Run 1 despite 1/7 of the statistics: analysis improved
Top-Higgs coupling with FCNC

Searching for flavor changing neutral currents with $t \to (u)cH$
- Process arising only at the loop level in the standard model (forbidden by GIM mechanism)
- Very small branching ratio: any excess would be a clear sign of new physics

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to u\gamma$</td>
<td>$3.7 \cdot 10^{-16}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \to uZ$</td>
<td>$8 \cdot 10^{-17}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \to uH$</td>
<td>$2 \cdot 10^{-17}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$5.5 \cdot 10^{-6}$</td>
<td>—</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$t \to c\gamma$</td>
<td>$4.6 \cdot 10^{-14}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \to cZ$</td>
<td>$1 \cdot 10^{-14}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \to cH$</td>
<td>$3 \cdot 10^{-15}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>$\sim 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>

Searches in $t\bar{t}$ production, followed by top FCNC decay with a Higgs boson

Anomalous $tH$ FCNC production not pursued yet.
CMS tH FCNC, Run I

CMS TOP-13-017, TOP-14-019, TOP-14-020 (paper to appear soon)

CMS tH FCNC analyses:
- $H \rightarrow \gamma\gamma$: background fit in hadronic and leptonic channels
- $H \rightarrow bb$: Reconstruction BDT, use NN as discriminant
- Multilepton: Cut based analysis

Limits of BR($t \rightarrow (u)cH$) at the 1% level or less (still orders of magnitude above MSSM predictions)

### Multilepton

<table>
<thead>
<tr>
<th></th>
<th>$-\sigma$</th>
<th>BR$_{exp}(t \rightarrow H c)$</th>
<th>$+\sigma$</th>
<th>BR$_{obs}(t \rightarrow H c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>trilepton</td>
<td>0.95</td>
<td>1.33</td>
<td>1.87</td>
<td>1.26</td>
</tr>
<tr>
<td>same-sign dilepton</td>
<td>0.68</td>
<td>0.93</td>
<td>1.26</td>
<td>0.99</td>
</tr>
<tr>
<td>combined</td>
<td>0.65</td>
<td>0.89</td>
<td>1.22</td>
<td>0.93</td>
</tr>
</tbody>
</table>

### $H \rightarrow bb$

<table>
<thead>
<tr>
<th></th>
<th>$t \rightarrow cH$ channel</th>
<th>$t \rightarrow uH$ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$73.9 \pm 108.7$(stat.$)\pm 24.4$(syst.)</td>
<td>$196.9 \pm 87.3$(stat.$)\pm 59.1$(syst.)</td>
</tr>
<tr>
<td>Total background</td>
<td>$6766 \pm 136.0$(stat.$)\pm 947.2$(syst.)</td>
<td>$6636 \pm 118.6$(stat.$)\pm 796.3$(syst.)</td>
</tr>
<tr>
<td>Observed events</td>
<td>6840</td>
<td>6840</td>
</tr>
<tr>
<td>Expected limit</td>
<td>0.89%</td>
<td>0.85%</td>
</tr>
<tr>
<td>Observed limit</td>
<td>1.16%</td>
<td>1.92%</td>
</tr>
</tbody>
</table>
ATLAS tH FCNC Run I and projections
JHEP 12 (2015) 061

- Similar analyses performed at ATLAS
- Exclusion limits \( \text{BR}(t \rightarrow (u)cH) < 0.45\% \)

Projections at HL-LHC \( L=3000 \text{ fb}^{-1} \)

ATLAS-PHYS-PUB-2016-019
- Semi-leptonic ttbar decay, \( H \rightarrow bb \)
- Reference scenario: tracker, muon \( |\eta|<4 \)
- Limits 50x better than at 8 TeV
- Approaching the range of 2HDM/MSSM predictions

\[
\begin{array}{c|ccc}
 & \text{t} \rightarrow Hu & \text{t} \rightarrow Hc & \text{t} \rightarrow Hu+Hc \\
\hline
\text{Reference scenario} & 1.2 \cdot 10^{-4} & 1.0 \cdot 10^{-4} & 0.55 \cdot 10^{-4}
\end{array}
\]

- Similar results \( \text{BR}(t \rightarrow cH) \sim 1.5 \cdot 10^{-4} \)
  with \( H \rightarrow \gamma \gamma \) from extrapolated 8 TeV results (ATLAS-PHYS-PUB-2013-012)
Conclusions

**ttH production**
- Sensitivity is already comparable or slightly better than Run I (able to reach ~40% precision on ttH signal strength with ATLAS and CMS 2015+2016 data), and results are consistent with Run I.
- More data is needed to evaluate if the Run I “excess” (though compatible with SM) is not a fluctuation.

**tHq searches with negative top-Higgs coupling**
- Run I tHq sensitivity was able to exclude <~3 the tHq cross section for Ct=-1.
- First 13 TeV measurements are being made available. H→bb sensitivity already comparable Run I dataset with 2015 data.

**Top quark FCNC decay with Higgs**
- Analyses performed at 8 TeV reach BR < 0.4%.
- Run II analyses are ongoing.

**2016 data taking period is still ongoing**!
Back-up slides
Most sensitive channel: 6 jets, 3 b

<table>
<thead>
<tr>
<th>Process</th>
<th>tH rate up/down [%]</th>
<th>ttH rate up/down [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy Scale</td>
<td>11.3/ -10.1</td>
<td>7.7/ -7.0</td>
</tr>
<tr>
<td>Jet energy Resolution</td>
<td>-0.1/ +0.1</td>
<td>-0.1/ +0.1</td>
</tr>
<tr>
<td>Pile-Up</td>
<td>-0.1/ +0.0</td>
<td>+0.1/ -0.2</td>
</tr>
<tr>
<td>Electron Efficiency</td>
<td>1.6/ -1.6</td>
<td>1.6/ -1.6</td>
</tr>
<tr>
<td>Muon Efficiency</td>
<td>1.2/ -1.2</td>
<td>1.2/ -1.2</td>
</tr>
<tr>
<td>b-Tag HF contamination</td>
<td>-3.5/ +8.4</td>
<td>+0.2/ +0.6</td>
</tr>
<tr>
<td>b-Tag HF stats (linear)</td>
<td>-6.4/ +6.2</td>
<td>-5.3/ +4.9</td>
</tr>
<tr>
<td>b-Tag HF stats (quadratic)</td>
<td>+4.2/ -4.4</td>
<td>+3.3/ -3.6</td>
</tr>
<tr>
<td>b-Tag LF contamination</td>
<td>+7.1/ -5.1</td>
<td>+5.5/ -4.2</td>
</tr>
<tr>
<td>b-Tag LF stats (linear)</td>
<td>-3.2/ +6.5</td>
<td>-0.6/ +1.1</td>
</tr>
<tr>
<td>b-Tag LF stats (quadratic)</td>
<td>+0.5/ +1.2</td>
<td>-0.8/ +1.1</td>
</tr>
<tr>
<td>b-Tag charm Uncertainty (linear)</td>
<td>-12.6/ +16.9</td>
<td>-0.6/ +0.7</td>
</tr>
<tr>
<td>b-Tag charm Uncertainty (quadratic)</td>
<td>+1.4/ -1.4</td>
<td>+0.0/ -0.0</td>
</tr>
<tr>
<td>Q2 scale (tt+lf)</td>
<td>-1.9/ +2.8</td>
<td>-</td>
</tr>
<tr>
<td>Q2 scale (tt+lf)</td>
<td>+0.6/ +0.9</td>
<td>-</td>
</tr>
<tr>
<td>Q2 scale (tt+2b)</td>
<td>-0.5/ +0.8</td>
<td>-</td>
</tr>
<tr>
<td>Q2 scale (tt+bb)</td>
<td>-0.9/ +1.3</td>
<td>-</td>
</tr>
<tr>
<td>Q2 scale (tt+c\bar{c})</td>
<td>-1.6/ +2.4</td>
<td>-</td>
</tr>
<tr>
<td>PS scale (tt+lf)</td>
<td>4.4/ -8.7</td>
<td>-</td>
</tr>
<tr>
<td>PS scale (tt+lf)</td>
<td>-1.3/ +0.8</td>
<td>-</td>
</tr>
<tr>
<td>PS scale (tt+2b)</td>
<td>-1.0/ +0.4</td>
<td>-</td>
</tr>
<tr>
<td>PS scale (tt+bb)</td>
<td>-2.0/ +1.3</td>
<td>-</td>
</tr>
<tr>
<td>PS scale (tt+c\bar{c})</td>
<td>-4.3/ +2.3</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 jets, 3 b-tags</td>
<td>14.5</td>
<td>18.6^{+8.2}_{-5.5}</td>
</tr>
<tr>
<td>4 jets, ≥4 b-tags high BDT output</td>
<td>35.7</td>
<td>25.6^{+13.4}_{-8.1}</td>
</tr>
<tr>
<td>4 jets, ≥4 b-tags low BDT output</td>
<td>86.6</td>
<td>84.2^{+41.3}_{-28.8}</td>
</tr>
<tr>
<td>5 jets, 3 b-tags</td>
<td>16.0</td>
<td>12.3^{+5.5}_{-3.6}</td>
</tr>
<tr>
<td>5 jets, ≥4 b-tags high BDT output</td>
<td>7.5</td>
<td>10.3^{+5.6}_{-3.4}</td>
</tr>
<tr>
<td>5 jets, ≥4 b-tags low BDT output</td>
<td>35.2</td>
<td>31.9^{+16.1}_{-9.9}</td>
</tr>
<tr>
<td>≥6 jets, 2 b-tags</td>
<td>25.4</td>
<td>41.1^{+21.1}_{-13.1}</td>
</tr>
<tr>
<td>≥6 jets, 3 b-tags</td>
<td>9.6</td>
<td>7.6^{+3.3}_{-2.2}</td>
</tr>
<tr>
<td>≥6 jets, ≥4 b-tags high BDT output</td>
<td>9.2</td>
<td>8.3^{+4.4}_{-2.7}</td>
</tr>
<tr>
<td>≥6 jets, ≥4 b-tags low BDT output</td>
<td>15.4</td>
<td>18.3^{+5.8}_{-3.5}</td>
</tr>
<tr>
<td>≥4 jets, ≥2 b-tags, boosted</td>
<td>7.5</td>
<td>10.7^{+5.9}_{-3.5}</td>
</tr>
<tr>
<td>lepton+jets combined</td>
<td>4.0</td>
<td>4.1^{+1.8}_{-1.2}</td>
</tr>
</tbody>
</table>
Background to ttH multi-lepton searches
- At 13 TeV, cross section ~x4 relative to 8 TeV
- ttW with 2lss: BDT using event kinematics: 3.9σ (2.6σ) observed (expected)
- ttZ with 3l,4l: counting events classified by jets/b-jets multiplicity: 4.6σ (5.8σ)
- ttW with 2lss (dimuon only), 3l: $2.2\sigma$ (1.0\sigma) observed (expected)
- ttZ with 3l (on-Z region included), 4l: counting events classified by jets/b-jets multiplicity: $3.9\sigma$ (3.4\sigma)
ttH multilepton: dimuon?
ATLAS-CONF-2016-058, CMS HIG-16-022

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1} \)

\( \ttW \) VR

Events

<table>
<thead>
<tr>
<th>Lepton flavor</th>
<th>Data</th>
<th>( \ttH ) (SM)</th>
<th>( \ttW )</th>
<th>Diboson</th>
<th>Non-Prompt</th>
<th>QM\text{MisReco}</th>
<th>Other</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
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<td>( \mu\mu )</td>
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<td>( e\mu )</td>
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<td>( ee )</td>
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</table>

CMS Preliminary
12.9 fb\(^{-1}\) (13 TeV)

Post-fit, \( \mu \)

Data
\( \ttH \)
\( \ttW \)
\( \tt(Z/\gamma^*) \)
Diboson
Non-Prompt
QM\text{MisReco}
Other
Fakes
Flips

Data/Pred.