Search for associated production of a Higgs boson with a single top quark

Ken Bloom
for the CMS Collaboration
6 August 2015
We all know the four favorite Higgs production mechanisms and tend to forget about another.

The SM cross section for single top plus Higgs production is $\sim 1000 \times$ smaller than that for gluon fusion.

$\sigma(tHq) = 18.3 \, \text{fb}$

Why even bother looking?
We all know the four favorite Higgs production mechanisms and tend to forget about another.

The SM cross section for single top plus Higgs production is \( \sim 1000 \times \) smaller than that for gluon fusion.

- \( \sigma(tHq) = 18.3 \text{ fb} \)

Why even bother looking?

Higgs cross sections 8TeV pp collisions:

- H: 100,000 fb
- Hqq: 10,000 fb
- HW: 1,000 fb
- HZ: 100 fb
- ttH: 10 fb
- tH: ?

- The SM cross section for single top plus Higgs production is ~1000x smaller than that for gluon fusion.
- \( \sigma(tHq) = 18.3 \text{ fb} \)
- Why even bother looking?
Discovery through interference

- Small cross section due to destructive interference between two diagrams
- Should the sign of the top Yukawa coupling be inverted \((y_t = -1)\), interference is constructive, and cross section is \(\times 13\) larger!
- \(y_t = -1\) disfavored, but not eliminated
- Composite Higgs, FCNC processes could enhance cross section further
CMS has completed four direct searches for the tHq process

- $H \rightarrow \gamma\gamma$: Smallest branching ratio but very pure; BR enhancement
- $H \rightarrow WW/\tau\tau$ multileptons: small branching ratio, non-prompt lepton backgrounds
- $H \rightarrow T_{had}T_{l}$: similar issues, smaller rate (new result!)
- $H \rightarrow bb$: Largest branching ratio but very large $t\bar{t}$ background

A number of commonalities among the searches:

- All searching for the anomalous ($y_t = -1$) production mode
- All take advantage of top-quark semi-leptonic decay
- All have $t\bar{t}$ as their most significant background
- Combined result takes inputs from all four channels (new result!)
H→γγ: selection

- Two high-pT photons
- Signal region 122 < m_{γγ} < 128 GeV
- Use sidebands for background estimate
- One isolated μ or e
- One b jet
- One forward jet
Resonant backgrounds from other processes with $H \to \gamma\gamma$

- Reduce with cut on likelihood discriminant formed from kinematic quantities distinguishing $t\bar{t}$ from $t$, estimate from simulations

Remaining backgrounds have smooth shape in $m_{\gamma\gamma}$

- Fit $m_{\gamma\gamma}$ spectrum with an exponential function, use higher-statistics control regions to estimate systematic uncertainties

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tHq, y_t = -1$</td>
<td>0.67</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$0.03 + 0.05$</td>
</tr>
<tr>
<td>$VH$</td>
<td>$0.01 + 0.01$</td>
</tr>
<tr>
<td>other $H$</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: yields include increases in $B(H \to \gamma\gamma)$ due to $y_t = -1$
Zero events in sidebands
Zero events in signal region
Set 95% CL upper limit of $4.1 \times \sigma_{tHq}(Y_t = -1)$
Observed limit coincides with expected limit

CMS HIG-14-001
Trilepton final state

- $\mu\mu\mu$, $\mu\mu e$, $\mu ee$, $eee$
- Exactly one b-tagged jet
- At least one forward non b-tagged jet
- Missing energy
- Z veto
Same-sign dilepton final state

- $\mu\mu$ and $e\mu$
- At least one $b$-tagged jet
- At least one central jet
- At least one forward non $b$-tagged jet
- Reject $\tau_{\text{had}}$
~ 1/2 background is from non-prompt leptons, mostly from **t¯t**

- Estimate rate with “tight-loose method,” fake rate taken from control samples and then applied to ID/isolation sideband regions

- Also account for charge mis-ID, get rate from **Z** events

- Discriminating likelihood formed from information on forward activity, jet and b-jet multiplicity, lepton kinematics/charge

### Prediction

<table>
<thead>
<tr>
<th></th>
<th>eµ</th>
<th>µµ</th>
<th>3l</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>3.3</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>106</td>
<td>53</td>
<td>42</td>
</tr>
</tbody>
</table>
Set limit through likelihood fit

Combine three channels

- Expected UL: $5.0^{+2.1}_{-1.4} \times \sigma_{tHq}(y_t=-1)$ at 95% CL
- Observed UL: $6.7 \times \sigma_{tHq}(y_t=-1)$ at 95% CL

Largest systematic uncertainties from non-prompt lepton rate estimate

---

**Search for tHq — K. Bloom**

8/6/15
H → ττ: selection

- Very much like the trilepton analysis, but use a hadronic τ
  - Same-sign eμ or μμ
  - Careful attention to lepton isolation, multivariate technique
  - Isolated τ_h, opposite sign
  - At least one b jet
H→ TT: backgrounds

- Largest background is from tt̅ with non-prompt leptons
- As in multilepton analysis, determine a fake rate and apply it in a sideband sample to estimate background level
- Linear discriminant to separate backgrounds, using properties of most-forward jet, b-jet properties, other kinematic variables
- Sample with inverted τ isolation used for training, validation

| Process         | eμτ
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>tHq, C_t = −1</td>
<td>0.42 ± 0.05</td>
</tr>
<tr>
<td>tHW, C_t = −1</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>ttH</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>ttV</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td>VV</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>Reducible</td>
<td>6.3 ± 3.1</td>
</tr>
<tr>
<td>Tot. background</td>
<td>9.5 ± 3.7</td>
</tr>
<tr>
<td>Data</td>
<td>5</td>
</tr>
</tbody>
</table>

| Process         | μμτ
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>tHq, C_t = −1</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>tHW, C_t = −1</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>ttH</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>ttV</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>VV</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Reducible</td>
<td>4.5 ± 1.9</td>
</tr>
<tr>
<td>Tot. background</td>
<td>5.4 ± 2.4</td>
</tr>
<tr>
<td>Data</td>
<td>7</td>
</tr>
</tbody>
</table>
Maximum likelihood fit to set limits

- Expect: \(< 1 \times 10^{+6.4} \times \sigma_{tHq}(y_t = -1)\) at 95% CL
- Observe: \(< 9 \times \sigma_{tHq}(y_t = -1)\) at 95% CL

Largest systematic uncertainties from non-prompt lepton estimate, but statistical uncertainties dominate

**CMS HIG-14-027**
**H → b¯b: selection**

- One isolated high-pT lepton
- Missing energy from ν
- Three or four b jets
- Extra non-b jet (either forward or higher in pT)
- Lots of t¯t background!

### Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 b jets</td>
<td>13/1900</td>
</tr>
<tr>
<td>4 b jets</td>
<td>1.4/66</td>
</tr>
</tbody>
</table>
Need to assign each of the jets to parent quarks of final state

Develop multivariate discriminator based event quantities such as invariant masses, $\Delta R$'s, jet $\eta$ and $p_T$ values, jet charges

Choose single best assignment of jets to quarks as reconstruction hypothesis

\textit{Do this separately under two different assumptions of initial state: tHq signal and $t \bar{t}$ background}

With tHq and $t \bar{t}$ reconstructions done, form kinematic quantities specific to each of the reconstructions and develop another discriminator based on them that distinguishes the two processes

Use templates in this variable to extract the tHq signal fraction

$t \bar{t}$ template from simulation, allowing $t \bar{t}$+HF fraction to vary

Verified with data-driven method that makes use of two-tag events, results are consistent
Expected upper limit: $5.2_{-1.7}^{+2.1} \times \sigma_{tHq}(y_t=-1)$ at 95% CL

Observed upper limit: $7.6 \times \sigma_{tHq}(y_t=-1)$ at 95% CL

Largest systematic uncertainties from $t\bar{t}$ modeling and b-tag efficiencies/mistag rates
- Put it all together in likelihood fit — many bins, parameters.
- Check sensitivity to $y_t = -1$, count any enhancement to tHq and $H \rightarrow \gamma\gamma$ as signal
- Expect $< 2.0 \times \sigma_{tHq}(y_t=-1)$, observe $2.8 \times \sigma_{tHq}(y_t=-1)$ at 95% CL
- Also, quote limit on $\sigma_{tHq}$ as a function of $B(H \rightarrow \gamma\gamma)$

---

<table>
<thead>
<tr>
<th>$\sigma_{95%}/\sigma_{y_t=-1}$</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow WW/T_tT_t$</th>
<th>$H \rightarrow T_tT_h$</th>
<th>$H \rightarrow b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td>4.1</td>
<td>5.0</td>
<td>11.4</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>4.1</td>
<td>6.7</td>
<td>9.8</td>
<td>7.6</td>
</tr>
</tbody>
</table>

---

**CMS**

$\sigma_{95\%}$ limits on $\alpha_{\text{QCD}}^{-1}$ for various models and processes.

---

**CMS HIG-14-027**

Search for tHq — K. Bloom

---

[Graphs and tables are shown, but not transcribed in the natural text format.]
Conclusions/Outlook

- tHq production rate is sensitive to the sign of the top Yukawa couplings and other new physics
- CMS has completed searches for tHq in four different final states
  - New result in the $H \rightarrow T_{\text{had}} T_{l}$ channel
  - Set cross section limit $< 2.8 \times \sigma_{tHq}(y_{t}=-1) @ 95\% \text{ CL with } 20 \text{ fb}^{-1}$
  - Combination is a new result
- Not yet sensitive to the anomalous production, but
  - $\sigma_{tHq}$ is x4 larger at 13 TeV, should have enough LHC data in 2016 to exclude (or discover?) the $y_{t}=-1$ hypothesis
  - Beyond that, can set limits in the $(\kappa_{f}, \kappa_{V})$ plane, have sensitivity to Higgs-mediated FCNC processes tHq with $q = u, c$, and more
- Interesting opportunities ahead for Run 2 in these searches!