Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV

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We all know the five favorite Higgs production mechanisms and tend to forget about another.

The SM cross section for single top plus Higgs production is \(~500\times\) smaller than that for gluon fusion.

- \(\sigma(tHq) = 71 \text{ fb}\)
- \(\sigma(tHW) = 16 \text{ fb}\)

Why even bother looking?
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Why even bother looking?

Higgs production in pp collisions at 13 TeV:

- ggF
- VBF
- WH
- ZH
- ttH
- tH

arXiv:1610.07922
Discovery through interference

- Small cross section due to destructive interference between two diagrams
  - Similar for tHW production
  - If the sign of the top Yukawa coupling is inverted ($\kappa_t = -1$), interference is constructive, and cross section is $\times 10$ larger!

- Most production modes depend on the square of the coupling, insensitive to sign
- Bounds on $\kappa_t$ largely derived from decays
  - Constraints assume no new particles in loops
  - Composite Higgs, FCNC processes could enhance cross section further
tH production has recently gained attention in the context of standard model effective field theory.

“opens up the rather unique possibility of accessing top-Higgs, top-gauge, triple gauge, gauge-Higgs interactions in the same final state.”


CMS Run 2 searches for tH

- Excellent opportunity to search for tH in LHC Run 2 data
  - CMS Run 1 result (JHEP 06 (2016) 177) only explored $k_t = -1$
  - tHq cross section $\sim \times 4$ larger at 13 TeV than 8 TeV
  - Include tHW as signal, improved analysis techniques, greater exploration of $k_t \neq -1$

- Two CMS searches for tH production (PRD 99 (2019) 092005)
  - $H \rightarrow WW$ multileptons: small branching ratio but better S/B, non-prompt lepton backgrounds
  - $H \rightarrow b\bar{b}$: Largest branching ratio but very large $t\bar{t}$ background

Commonalities:
- Both take advantage of top semi-leptonic decay and forward light jet
- Both have $t\bar{t}$ (including $t\bar{t}H$) as their most significant background

Plus: reinterpretation of $H \rightarrow \gamma\gamma$ in the tHq context
**H → WW → leptons: selection**

- **Trilepton final state**
  - $\mu\mu\mu$, $\mu\mu e$, $\mu ee$, $eee$
  - Z veto

- **Same-sign dilepton final state**
  - $\mu\mu$, $\mu e$

- **Both cases**
  - At least one b-tagged jet
  - At least one non-tagged jet

- $\sim 75\% \ H \rightarrow WW$, $\sim 20\% \ H \rightarrow ZZ$, $\sim 5\% \ H \rightarrow \tau\tau$

- Significant fraction of selected data events also pass selections for $ttH$ analysis, counted as signal
Two dominant sources of background

- $\bar{t}t^+ (W/Z/H/\gamma)$ with prompt leptons
  - Modeled with simulations
- $\bar{t}t$ with non-prompt leptons
  - Modeled with data using loose-to-tight extrapolation from control regions

Separate multivariate discriminators for two main backgrounds, using info on jet and b-jet multiplicities, forward jet activity and kinematic properties of leptons

Combine information from two discriminators into one variable

### Prediction

<table>
<thead>
<tr>
<th></th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
<th>$3l$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong> ($\kappa_t = -1$)</td>
<td>39</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td><strong>ttH</strong> ($\kappa_t^2 = 1$)</td>
<td>35</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>443</td>
<td>211</td>
<td>106</td>
</tr>
</tbody>
</table>
Classifier output distributions from combined maximum likelihood fit

Uncertainties dominated by normalization of non-prompt lepton backgrounds, scale variations for $t\bar{t}V$ and $t\bar{t}H$ processes, lepton selection efficiencies
One isolated high-pT lepton
- Missing energy from $\nu$
- Three or four $b$ jets
- One additional jet
- Lots of $t\bar{t}$ background!

<table>
<thead>
<tr>
<th>Sample</th>
<th>$S(\kappa_t = -1)/B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 b jets</td>
<td>252/45300</td>
</tr>
<tr>
<td>4 b jets</td>
<td>32.8/1880</td>
</tr>
</tbody>
</table>
Need to assign each of the jets to parent quarks of final state

- Develop multivariate discriminator based on event quantities such as invariant masses, $\Delta R$'s, jet $\eta$ and $p_T$ values, jet charges and tagging info
- Choose single best assignment of jets to quarks as reconstruction hypothesis

*Do this separately under three different assumptions of initial state: $t\bar{t}q$ and $t\bar{t}W$ signal and $t\bar{t}$ background*

With $t\bar{t}$ 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 processes

- Validated in two-tag event sample, enriched in $t\bar{t}$
- Fit distribution of that discriminator to templates from signal and background
- Simultaneously, use a $t\bar{t}$-enriched dilepton sample to constrain the heavy flavor content of the $t\bar{t}$ background, using (yet) another discriminator
Classification discriminator from maximum likelihood fit

- Dominant systematic uncertainties from renormalization and factorization scales, overall normalization of $t\bar{t}+HF$ processes, and jet energy corrections
Reinterpretation of $H \rightarrow \gamma\gamma$

- $tH$ already included in CMS inclusive $H \rightarrow \gamma\gamma$ analysis (JHEP 11 (2018) 185), with events mostly populating the “$ttH$ hadronic” and “$ttH$ leptonic” categories

- Use these categories to constrain $K_t$ and $tH$ production cross section
  
  $K_t$, $K_V$ affect $tH$ and $ttH$ cross sections and Higgs branching fractions

- Correct changes in acceptance as a function of $K_t/K_V$ due to changes in kinematics
Constraints on Higgs couplings

- tH production cross sections go as
  \[ \sigma_{tHq} = (2.63\kappa_t^2 + 3.58\kappa_V^2 - 5.21\kappa_t\kappa_V)\sigma_{SM}^{tHq}, \]
  \[ \sigma_{tHW} = (2.91\kappa_t^2 + 2.31\kappa_V^2 - 4.22\kappa_t\kappa_V)\sigma_{SM}^{tHW} \]

- Perform profile likelihood scan as a function of \( K_t \) (with \( K_V = 1 \)), which affects tH and \( t\bar{t}H \) cross sections and Higgs branching fractions

- Expect to favor \( K_t = 1 \) over \( K_t = -1 \) by 4\( \sigma \), exclude \( K_t \) outside \([-0.5, 1.6]\) at 95% CL

- Data favor \( K_t > 0 \) over \( K_t < 0 \) by 1.5\( \sigma \), exclude \( K_t \) outside \([-0.9, -0.5]\) and \([1.0, 2.1]\) at 95% CL

- 2\( \sigma \) excess of events over expectations in multilepton and \( \gamma\gamma \) channels; combined \( tH + t\bar{t}H \) rate is \( (2.00 \pm 0.53) \times \text{SM} \) expectations

- Consistent with dedicated \( t\bar{t}H \) searches
Introduce separate signal strength parameter for tH, excluding ttH

Fix ttH to its $\kappa_t$-dependent cross section

Expected limit of $12 \times$ SM production cross section; observe limit of $25 \times$ SM
Results presented are derived from data collected in 2016

Full Run 2 (2016-18) result will be more strongly integrated with $\bar{t}tH$ result, as there are significant overlaps in the event selection

Other analyses:
- $tH$ cross section is also sensitive to Higgs CP mixing phase, expect to set limits on admixture of CP-odd Higgs in future analyses
- Search for Higgs-mediated FCNC process $tHq$ with $q = u, c$
- Very (very?) far future: $tHHq$ has strong dependence on Higgs self coupling, but unfortunately an extremely small cross section
- Much to learn yet from this process at the center of everything!