Search for electroweak production of a vectorlike quark decaying to a top quark and a Higgs or Z boson using boosted topologies in an all-hadronic final state

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Vector like Quarks

Heavy quark, spin $\frac{1}{2}$
- Chiralities transform the same under SM gauge group

Contained in various SM extensions
- Such as Little Higgs, Composite Higgs

Why VLQs?
- Potential solution to hierarchy problem
- Conventional 4th generation is excluded
- Mass not constrained by Yukawa coupling

For this talk:
- top partner, charge $+2/3$

<table>
<thead>
<tr>
<th>VLQ Type</th>
<th>Charge</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>$+2/3$</td>
<td>$bW^+, tH, tZ$</td>
</tr>
<tr>
<td>B</td>
<td>$-1/3$</td>
<td>$tW^-, bH, bZ$</td>
</tr>
<tr>
<td>X</td>
<td>$5/3$</td>
<td>$tW^+$</td>
</tr>
<tr>
<td>Y</td>
<td>$-4/3$</td>
<td>$bW^-$</td>
</tr>
</tbody>
</table>
Types of Production

Single
- Mediated by electroweak interaction
- Model dependent cross section
  - Relies on coupling at production vertex
  - Dominates with higher masses (above 1 TeV)
- Our range $\Rightarrow M(T) = 1000$-$1800$ GeV

In Pairs
- Mediated by strong interaction
- Model independent cross sections
  - Relies on strong coupling
Single T→tH/Z

Two single production modes explored:
- \( pp \rightarrow T bq \), charged current
- \( pp \rightarrow T tq \), neutral current
- All hadronic decay: \( H/Z \rightarrow b\bar{b}, t \rightarrow bW \)
- Left and Right handed couplings

Cross sections:
- Evaluated using Simplest Simplified Model, \texttt{arXiv:1409.0100}
- Depends quadratically on scaling factors: \( c_{bW}, c_{tZ} \) (for tH case)
- \( pp \rightarrow T bq \): 0.174-1.950 pb for \( M(T) = 1000-1800 \) GeV
- \( pp \rightarrow T tq \): 0.0324-0.285 pb for \( M(T) = 1000-1800 \) GeV

Full decay mode
Boosted Jets with Fully Hadronic Decay Mode

Above 1 TeV masses, jets become Lorentz boosted
- Decays are fully merged into a single jet
- Can use substructure techniques for tagging jets

Substructure Used:
- Jet mass grooming
- N-subjettiness ($\tau_2/\tau_1$, $\tau_3/\tau_2$)
  - Higgs → two hard subjets (small $\tau_2/\tau_1$)
  - top → three hard subjets (small $\tau_3/\tau_2$)
Jet Tagging with Substructure

Jet Mass grooming $\rightarrow$ help identify H, t jets
- Pruned
  - $\left(\frac{\min(p_T1,p_T2)}{p_Tp}\right) > 0.1; \Delta R_{12} < 0.5 \times \frac{m_{jet}}{p_T}$
- Soft Drop
  - $\left(\frac{\min(p_T1,p_T2)}{p_T1+p_T2}\right) > z_{cut} (\frac{\Delta R_{12}}{R_0})^\beta; z_{cut} = 0.1, \beta = 0$

N-subjettiness
- Discriminate against multijet background
- Multijet $\rightarrow$ large $\tau_2/\tau_1$ and $\tau_3/\tau_2$

Subjet b-tagging
- Combined Secondary Vertex algorithm
- Combination of track, secondary vertex variables

Re-clustering removes soft large angle constituents

De-cluster iteratively
Stop when criterion satisfied
Analysis Cuts

2.3 fb⁻¹ pp collision data at $\sqrt{s} = 13$ TeV collected in 2015 by CMS

Events selected by 2-stage trigger
- Level 1 → loose jet requirements
- High Level Trigger (HLT)
  - Scalar sum of jet $p_T > 800$ GeV required

Jet candidates from HLT reconstructed with anti-$k_T$ algorithm, R=0.4, 0.8 (labeled AK4, AK8 respectively)

Main Selection:
- At least 4 AK4 jets → $p_T > 30$ GeV, $|\eta| < 5$
- At least 1 AK8 jet → $p_T > 300$ GeV, $|\eta| < 2.4$
- Scalar sum of AK4 jet $p_T$ ($H_T$) > 1100 GeV

1 Higgs tagged jet:
- Pruned Mass → 105-135 GeV (Z → 65-105 GeV)
  - $\tau_2/\tau_1 < 0.6$
  - 2 subjet b-tags

1 Top tagged jet:
- Soft drop mass → 110-210 GeV
  - $\tau_3/\tau_2 < 0.54$
  - 1 subjet b-tag

$\Delta R$(Higgs, top) > 2.0
Mass of T after selection

Shown is the simulated M(T) distribution for 1000, 1200, 1500, and 1800 GeV mass points, after all cuts;

$\sigma^B(T \rightarrow tH)$ set to 1 pb

$p\bar{p}\rightarrow Tbq$ on solid lines; $p\bar{p}\rightarrow Ttq$ on dotted

Left handed coupling shown, which uses the $c_L^{bW}$ scaling factor
Background Estimation

Backgrounds Considered
- **QCD Multijets** → estimated with data
- **$t\bar{t} +$ jets** → estimated with MC
- **W + jets**
- **tW Single Top**

**Bold** → main backgrounds

ABCD Method used to estimate QCD background from data
- Predicts QCD background number and shape
- $N \rightarrow$ MC background subtracted from data in each region

Number Prediction:

$$\frac{N_D}{N_B} = \frac{N_C}{N_A} \rightarrow N_D = N_B \times \frac{N_C}{N_A}$$

Shape Prediction:

$$F_D = F_B \times \frac{N_C}{N_A}$$

**Anti-Higgs jet** → same as Higgs jet, but failing subjet b-tagging

<table>
<thead>
<tr>
<th>Region</th>
<th>N(Higgs tag)</th>
<th>N(anti-Higgs tag)</th>
<th>N(top tag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>&gt;0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>&gt;0</td>
<td>&gt;0</td>
</tr>
<tr>
<td>C</td>
<td>&gt;0</td>
<td>≥0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>&gt;0</td>
<td>≥0</td>
<td>&gt;0</td>
</tr>
</tbody>
</table>
Background and Data in good agreement, within estimated uncertainties

Uncertainty shown in table is the combined statistical and systematic

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated QCD</td>
<td>$10.8 \pm 5.5$</td>
</tr>
<tr>
<td>Estimated $t\bar{t}+\text{jets}$</td>
<td>$24.3 \pm 8.1$</td>
</tr>
<tr>
<td>Estimated $W+\text{jets}$</td>
<td>$0.6 \pm 0.6$</td>
</tr>
<tr>
<td>Estimated Background</td>
<td>$35.7 \pm 5.6$</td>
</tr>
<tr>
<td>Observed Events</td>
<td>30</td>
</tr>
</tbody>
</table>
T→tH, Limits

\[ \sigma(pp \to Tq)BR(T \to tH) \]

**Model:**
\[ c_L^{bw} = 0.5, \quad BR(tH) = BR(bW)/2 \]

\[ \sigma(pp \to Tq)BR(T \to tH) \]

**Model:**
\[ c_R^{tZ} = 0.5, \quad BR(tH) = BR(tZ) \]
Conclusion

Search performed for a single T quark, $T \to tH$, all hadronic decay

Using 3.2 fb$^{-1}$ pp collision data at 13 TeV collected by CMS, upper limits placed on $\sigma B(T \to tH)$

- 0.31-0.93 pb for M(T) ranging from 1000-1800 GeV
- [arXiv:1612.05336v2](https://arxiv.org/abs/1612.05336v2)

Future analysis in this channel planned for combined 2016, 2017 datasets
Backup
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Variation</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.7%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>PU reweighting</td>
<td>5%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$t\bar{t}$+jets cross section</td>
<td>6%</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>W+jets cross section</td>
<td>3.8%</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>PDF</td>
<td>1-3%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Higgs jet selection</td>
<td>10%</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$\tau_2/\tau_1$ scale factor</td>
<td>12.5%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Higgs mass JES</td>
<td>2%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Top mass JES</td>
<td>2%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>JES and JER</td>
<td>Shape (1-2%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Top-tagging</td>
<td>Shape (15-30%)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$H_T$ reweighting</td>
<td>Shape (1-3%)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>B-tag scale factor</td>
<td>Shape (2-5%)</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>