SEARCHES FOR VECTOR-LIKE QUARKS AT CMS
Vector-like quarks

- Fourth generation quarks (t’ and b’)
- Symmetric chiralities under SU(2)
  - Right and left-handed chiral state transform the same way
- Mass independent of Higgs coupling
  - Some models uses VLQs as a solution to the hierarchy problem.
  - Fermionic top partners can cancel contributions to Higgs mass
Four CMS searches are presented using 19.7 fb-1 of 8 TeV pp collisions

- Pair-produced $b' \rightarrow bH ; H \rightarrow bb$
  - Signal samples produced for $M(b') = 500, 600, 700, 800, 900, 1000, 1200$ GeV

- Pair-produced $b' \rightarrow tW, bZ, bH; $ Combined analysis
  - Signal samples produced for $M(b') = 500 – 1000$ GeV

- Pair-produced $t' \rightarrow tH ; $ all hadronic (jet substructure)
  - Signal samples produced for $M(t') = 500, 700, 1000$

- Pair-produced $t' \rightarrow tH ; H \rightarrow \gamma\gamma$
  - Signal samples produced for $M(t') = 700$
Object reconstruction

- Particles reconstructed using the “Particle Flow” algorithm
- Jets clustered using the anti-
  kT algorithm (R < 0.5) (AK5)
- Additional jets reconstructed using Cambridge-Aachen algorithm (R < 0.8) (CA8)
- b-Jets are identified using the Combined Secondary Vertex (CSV) method

The Higgs bosons from b’ decays are expected to be highly boosted, resulting in a small opening angle between the b-jets. This allows the bb pair to be reconstructed as a single jet.

Robert Stringer -- Univ. of Kansas    DPF2015
b' -> bH

- **Trigger Selection**
  - Sum of transverse momentum from reconstructed jets \( (H_T) > 750 \text{ GeV} \) (nearly 100% efficient)

- **Event Selection**
  - One Higgs Tagged Jet
    - CA5 Jet \( (p_T > 300 \text{ GeV}) \)
    - Jet substructure compatible with two jets
  - One b-tagged jet \( p_T > 80 \text{ GeV} \)
  - \( HT > 950 \text{ GeV} \)
Dominant background is QCD Multijet
- Additional contribution from tt +jets

ABCD method categorizes events into four sidebands
- Higgs tagged events; 90 < M < 140 (Signal)
- Higgs tagged events; M < 140 GeV (Bkg.)
- Anti-Higgs tagged; 90 < M < 140 (Bkg.)
- Anti-Higgs tagged; M < 140 GeV (Bkg.)

In the signal region, using a 0-b control sample, the predicted bkg. matches data.
### Results

- Simultaneous fit to 1b and ≥2 b categories.
- Upper limit of 846 GeV on the b’ quark mass is observed.
  - 95% confidence level.
  - Expected 811 GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>Yields after full selection</th>
<th>Yields in 1 b-tagged category</th>
<th>Yields in ≥ 2 b-tagged category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-driven background</td>
<td>872^{+49}_{-55} 903</td>
<td>825^{+47}_{-52} 860</td>
<td>46^{+4}_{-11} 43</td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing CMS Preliminary results with observed and expected limits.](image)
Five channel search (Legacy comb. of Run I Analyses)

Events categorized by number of leptons

$S_T$: Sum of transverse mom. from jets, leptons, missing E.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Additional Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton + Jets</td>
<td>4 Jets</td>
</tr>
<tr>
<td>Same Sign Dilepton</td>
<td>4 Jets</td>
</tr>
<tr>
<td>Opp. Sign Dilepton</td>
<td>1 b-jet</td>
</tr>
<tr>
<td>Multilepton</td>
<td>$M(\ell\ell) &gt; 12$ GeV</td>
</tr>
<tr>
<td>All hadronic</td>
<td>1 H tagged CA8 jet</td>
</tr>
</tbody>
</table>
Backgrounds show good agreement with data.
Upper limit set on $M(b')$

| $B \to tW$ | 890 | 880 |
| $B \to bH$ | 810 | 900 |
| $B \to bZ$ | 740 | 750 |

CMS

$B \to tW$ 100%

$B \to bH$ 100%

$B \to bZ$ 100%
t' -> tH; all hadronic

- Jet substructure methods
  - t Tagging and H tagging
  - Uses CA15 jets (better perf.)

- Trigger Selection
  - $H_T > 720$ GeV

- Event Selection
  - At least one t tag w/b subjet ($p_T > 200$ GeV)
  - At least one H tag w/two b subjets ($p_T > 150$ GeV)
Background Estimation

- tt background is simulated
- QCD multijet is estimated from data using ABCD method
  - Sideband B is obtained by inverting t tagger
  - Sideband C* is obtained by inverting the H tagger
  - Sideband A is obtained by inverting both taggers
  - Region D is signal with all tagging requirements

*tt contamination (~8%) is subtracted from sideband

Robert Stringer -- Univ. of Kansas  DPF2015
Events are divided into single H tag and multiple H tag categories

- Upper limit of 745 GeV for $M(t')$

Data matches bkg. estimation for single and multiple H tags.

No signal observed.
t' -> tH

- **Two search channels defined:**
  - **Leptonic**
    - Two Photons
    - One Isolated high-pT e/µ
    - ≥2 jets
    - \(H_T > 770\) GeV
  - **Hadronic**
    - Two Photons
    - No Isolated e/µ
    - ≥1 b-tag, ≥2 jets
    - \(H_T > 1000\) GeV
Data-driven background is obtained from diphoton mass distribution

- $100 < m_{\gamma\gamma} < 180$ GeV

- Leptonic and Hadronic done separately
No excess is observed

- Observed limit for $t't'$: 540 GeV
- Expected limit: 607 GeV

Data is normalized to the expected cross-section
Run 2 at the LHC is at higher energy (13 TeV)
- Will include single production t'/b'
- Use H/t taggers for boosted topologies
Search for pair-produced vector-like quarks of charge $-1/3$ decaying to $bH$ using boosted Higgs jet-tagging in pp collisions at $\sqrt{s} = 8$ TeV

Search for pair-produced vector-like $B$ quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV

Search for vector-like $T$ quarks decaying to top quarks and Higgs bosons in the all-hadronic channel using jet substructure

Search for vector-like top quark partners produced in association with Higgs bosons in the diphoton final state