Searches for Bottom-like 4\textsuperscript{th} Generation Quarks at CMS

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The CMS Collaboration

CERN Theory Institute – From the LHC to Future Colliders
13 February 2009
Introduction: 4\textsuperscript{th} Generation Quarks

- The Standard Model: At least three generations of quarks are required for CP violation, however...
  - CPV is far too small by 10 orders of magnitude.
  - An extra family of quarks may resolve this big gap. (Hou, arXiv:0803.1234)

- Direct measurement of Invisible Z width: $N_V = 2.92 \pm 0.05$, but
  - It does not guarantee that $N(\text{gen}) = 3$ exactly, e.g. heavy neutrino with mass $> 0.5M_Z$.

- Experimental limits from Tevatron direct searches:
  - $M(t' \rightarrow qW) > 311$ GeV/c\textsuperscript{2}.
  - $M(b' \rightarrow bZ) > 268$ GeV/c\textsuperscript{2} (assuming 100% $b' \rightarrow bZ$, so it's not really firm).
    Also there are some searches for long lived $b'$ decay, with 2D limits on $M(b')$ and $c\tau$ plane.

Today we are focusing on the bottom-like 4\textsuperscript{th} generation quark, $b'$. 
Introduction: 4th Generation Quarks

Decay “pattern” of the $b'$ quark

**Rich Signatures**

- Larger x-sec.
- For sizable $|V_{cb'}|$: $b' \to cW \gg t^{(*)}W^{(*)}$
- Suppressed $|V_{cb'}|$: $b' \to cW \ll t^{(*)}W^{(*)}$
- FCNC: $b' \to bZ, bH$

LHC provides the chance for direct searches, from light to heavy!

(today's topic)
Introduction: 4\textsuperscript{th} Generation Quarks

Heavy $b' =$ A bottom-like quark that decays to top and $W$. (Mass $> 255$ GeV)

- Full decay chain: $b'b' \rightarrow tW tW \rightarrow bbW^+W^-W^+W^-$ (4 $W$-bosons!)
- Possible final states: $4L+2J$, $3L+4J$, $2L+6J$, $1L+8J$, $0L+10J$
  \textit{(clean & large modes first)}

<table>
<thead>
<tr>
<th>Production yields @ 100/pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(W \rightarrow l\nu) = 1/3$</td>
</tr>
<tr>
<td>$\text{BR}(W \rightarrow jj) = 2/3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M(b')$ (GeV)</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(4L)</td>
<td>38</td>
<td>18</td>
<td>9</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td><strong>N(3L)</strong></td>
<td>307</td>
<td>143</td>
<td>71</td>
<td>38</td>
<td>22</td>
</tr>
<tr>
<td>N(2L)</td>
<td>920</td>
<td>429</td>
<td>212</td>
<td>115</td>
<td>65</td>
</tr>
<tr>
<td><strong>same-sign 2L</strong></td>
<td>307</td>
<td>143</td>
<td>71</td>
<td>38</td>
<td>22</td>
</tr>
<tr>
<td>N(1L)</td>
<td>12.3k</td>
<td>572</td>
<td>283</td>
<td>153</td>
<td>86</td>
</tr>
</tbody>
</table>

Smaller Standard Model background is expected for same-sign 2L.
The Analysis: $b' \to tW$ Searches

- **Data set assumption:**
  100 pb$^{-1}$ at 14 TeV recorded by the CMS detector.

- **Trigger:** single “relax” electron trigger + single loose muon trigger.

- **Lepton selections:**
  - **Electrons:** cut-based ID, isolated from tracks, $p_T > 20$ GeV/c.
  - **Muons:** must be isolated from tracks, $p_T > 20$ GeV/c.

  Requiring exact **2L with the same charge**, or **3L** in the final state.

- **Jet selections:** Iterative cone algorithm of 0.5 radius
  - **Same-sign 2L:** at least 4 or more jets $p_T > 35$ GeV/c.
  - **3L:** at least 2 or more jets $p_T > 35$ GeV/c.

- **Other requirements:**
  - **Missing ET:** MET $> 40$ GeV.
  - **A Z-boson veto:** $|M(\ell^+\ell^-)-M_Z| > 10$ GeV/$c^2$.
  - **Objects isolation:** $\Delta R(\ell,\ell) > 0.3$ & $\Delta R(\ell,\text{jet}) > 0.3$
The Analysis: $b' \rightarrow tW$ Searches

Expected Yields @ 100/pb

**$b'$ Signal** Assuming 100% $b' \rightarrow tW$

<table>
<thead>
<tr>
<th>M($b'$) (GeV)</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(3L)</td>
<td>23.6</td>
<td>7.6</td>
<td>2.9</td>
</tr>
<tr>
<td>N(same-sign 2L)</td>
<td>44.7</td>
<td>14.6</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>68.2</strong></td>
<td><strong>22.2</strong></td>
<td><strong>8.0</strong></td>
</tr>
<tr>
<td>S/N</td>
<td><strong>9.3</strong></td>
<td><strong>3.0</strong></td>
<td><strong>1.1</strong></td>
</tr>
</tbody>
</table>

- The signal is very significant, high S/N with 300 GeV/$c^2$.
- Good sensitivity up to 400 GeV/$c^2$.
- Background is dominated by the $tt+jets$ events.

**Background Sources**

<table>
<thead>
<tr>
<th>Process</th>
<th>tt+nj</th>
<th>ttZ(+j)</th>
<th>ttW(+j)</th>
<th>ttWW</th>
<th>Z/W+nj</th>
<th>WZ/ZZ</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(3L)</td>
<td>1.0</td>
<td>0.38</td>
<td>0.31</td>
<td>0.014</td>
<td>&lt;1.4</td>
<td>0.21</td>
<td>1.9</td>
</tr>
<tr>
<td>N(same-sign 2L)</td>
<td>4.7</td>
<td>0.31</td>
<td>0.43</td>
<td>0.020</td>
<td>&lt;1.4</td>
<td>&lt;0.11</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>5.7</strong></td>
<td><strong>0.69</strong></td>
<td><strong>0.74</strong></td>
<td><strong>0.035</strong></td>
<td>&lt;1.4</td>
<td><strong>0.21</strong></td>
<td><strong>7.3</strong></td>
</tr>
</tbody>
</table>

QCD events are negligible (<0.3 events)
Resulting Figures (for 300 GeV/c^2 b')

Signal observable:
\[ HT = \sum \mathbf{p}_T(\text{jets}) + \sum \mathbf{p}_T(\text{leps}) + \text{MET} \]
(carries mass information!)

Histograms are normalized to 100/pb luminosity

Background, mainly tt+jets
Background Estimation with Data

- Background is normalized by the control sample:
  **Opposite sign 2L w/ the same jet requirement**

  *(It's totally dominated by ttbar – as our wish!)*

- Z-veto is still applied.

- Governed by the probability to
  - observe a sign-flipped lepton *(become same-sign 2L)*
  - find an extra (fake) lepton *(become 3L)*

- Signal yield is obtained by an iteration method.
- Next slide.
Number of signal events is resolved by an iteration method:

- **Signal Region**: \( N \)
- **Control Region**: \( N_{\text{control}} \)

\[
N_B = N_{\text{control}} \times R_B = N_{\text{control}} \times R_B
\]

\[
N_S = N - N_B
\]

- Attribute all the events in the control region are background.
- Resolve the signal/background yields in the signal region:

- If we have signal, calculate the signal yield in the control region with \( R_S \):

\[
N_{\text{control}} = N_S / R_S
\]

- Subtract the signal in the control region, re-calculate the signal & background yields until it converged.
The ratios ($R_S$, $R_B$) used in the background estimation is the dominant systematic source.

<table>
<thead>
<tr>
<th>$M(b')$ (GeV)</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>11%</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>Non-prompt &amp; fake leptons</td>
<td>+7/−17%</td>
<td>+19/−47%</td>
<td>+51/−124%</td>
</tr>
<tr>
<td>Background cross sections</td>
<td>1%</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>11%</td>
<td>14%</td>
<td>27%</td>
</tr>
<tr>
<td>Jet efficiency</td>
<td>5%</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Missing energy</td>
<td>30%</td>
<td>20%</td>
<td>21%</td>
</tr>
<tr>
<td>Leptons</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Pile-ups</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Parton distribution function</td>
<td>5%</td>
<td>7%</td>
<td>9%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>4%</td>
<td>8%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Sum: systematics</strong></td>
<td><strong>+36/−39%</strong></td>
<td><strong>+35/−55%</strong></td>
<td><strong>+67/−132%</strong></td>
</tr>
<tr>
<td>Statistics (100 pb$^{-1}$)</td>
<td>15%</td>
<td>28%</td>
<td>57%</td>
</tr>
</tbody>
</table>

All the systematic uncertainties are determined assuming the early condition.
Counting Significance

HT Distributions for 300, 400, 500 GeV/c^2 b' signals

<table>
<thead>
<tr>
<th>M(b') (GeV)</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>b'b LO cross section (pb)</td>
<td>34.9</td>
<td>8.05</td>
<td>2.45</td>
</tr>
<tr>
<td>Signal Yield</td>
<td>68.2</td>
<td>22.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Background Yield</td>
<td>7.3</td>
<td>+10.5/−4.8 (syst.)</td>
<td></td>
</tr>
<tr>
<td>Significance (stat.+syst.)</td>
<td>7.5σ</td>
<td>2.0σ</td>
<td>0.0σ</td>
</tr>
</tbody>
</table>

Very significant (7.5σ) if M(b') = 300 GeV/c^2.
Not significant at all for 500 GeV/c^2, since background error > signal.

Background is independent of b' mass.
In the case of no signal observed in data, we could set the exclusion limit accordingly at 95% C.L.

We use a Bayesian limit for null hypothesis tests, with all the systematic effects are included. By comparing to the Pythia LO X-secs:

For 30/pb, $M(b') < 420$ GeV could be excluded.

For 100/pb, $M(b') < 480$ GeV could be excluded.
Summary & Conclusion

We have performed the feasibility study for a search of 4th generation bottom-like quark, $b' \rightarrow tW$, assuming a data set of 100 pb$^{-1}$ at 14 TeV at CMS. The systematic uncertainties at early condition are considered:

- If the $b'$ quark is as light as 300 GeV/$c^2$, the expected signal yield is 68 events, against 7.3 background events.
- A 7.5σ discovery can be carried out for a 300 GeV/$c^2$ $b'$ signal, using a simple counting experiment.
- Or, we could exclude such $b' \rightarrow tW$ signal up to $M(b')<480$ GeV at 95% confidence level if only SM processes observed.

Other possible decay channels are working in progress.

Looking forward to the first data from LHC.