Search for Fourth Family Quarks at ATLAS

E. Özcan, S. Sultansoy, G. Ünel
University College London,
Gazi University, Ankara,
CERN & University of California, Irvine

Flavour in the era of LHC workshop
Oct 9-11, 2006, CERN
Motivation: Yukawa Couplings in SM

• Masses of fermions introduced by couplings to Higgs field:
  \[ m_f = g_f \cdot \eta \quad (\eta = \langle H \rangle \approx 245 \text{ GeV}) \]

• Couplings vary by orders of magnitude:
  – Even among same type fermions:
    \[ \frac{g_t}{g_u} \approx 35000 : 175000 \]
    \[ \frac{g_b}{g_d} \approx 300 : 1500 \quad \frac{g_\tau}{g_e} \approx 3500 \]
  – Or within 3\textsuperscript{rd} family:
    \[ \frac{g_t}{g_b} \approx 40 \quad \frac{g_t}{g_\tau} \approx 100 \quad \frac{g_t}{g_{\nu_\tau}} > 10000 \]

• Three-family case not particularly natural.
Flavor Democracy

• Before spontaneous symmetry breaking, all fermions are massless. Fermions with same quantum numbers are indistinguishable.
• No reason why Yukawa couplings for fermions of a given type should be different.

\[
\begin{align*}
    a^d_{ij} &\approx a^d, \\
    a^u_{ij} &\approx a^u, \\
    a^l_{ij} &\approx a^l, \\
    a^\nu_{ij} &\approx a^\nu.
\end{align*}
\]

=> For each type of fermion (f = u, d, l, \(\nu\)), (n-1) massless particles and a single massive particle with \(m = n \cdot a^f \cdot \eta / \sqrt{2}\).
Flavor Democracy II

• With a single Higgs doublet responsible for all the masses, assume couplings for different types of fermions are comparable to each other and lies somewhere between the other couplings of EW unification:

\[ a^d \approx a^u \approx a^l \approx a^\nu \approx a \]

\[ e = g_w \sin \theta_w < \frac{a}{\sqrt{2}} < g_z = \frac{g_w}{\cos \theta_w} \]

• With these assumptions, flavor democracy predicts a fourth family with quasi-degenerate up-type \( u_4 \) and down-type \( d_4 \) quarks in the mass range \( \sim 300 \) to \( \sim 700 \) GeV (Ciftci, Ciftci, Sultansoy, PRD 72, 053006, 2005). This range is consistent with partial-wave unitarity at high energies.
Event Generation

- 12k signal events each generated for three choices of mass 250, 500, 750 GeV. (CompHEP v4.4.3)
  \[ pp \rightarrow d_4 \bar{d}_4 \rightarrow W^+W^- j j, \quad j = u, c \]
- Assume that mixing is predominantly to light (1st & 2nd) generations. Taking into account the current limits on the mixing parameters:
  \[ |V_{ud_4}| < 0.004 \quad |V_{cd_4}| < 0.044 \quad |V_{u_4d}| < 0.08 \quad |V_{u_4s}| < 0.11 \]
  A common mixing parameter of 0.001 is chosen for event generation (relative magnitudes not important).

<table>
<thead>
<tr>
<th>( M_{d_4} ) (GeV)</th>
<th>250</th>
<th>500</th>
<th>750</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma ) (MeV)</td>
<td>0.01</td>
<td>0.08</td>
<td>0.28</td>
</tr>
<tr>
<td>( \sigma ) (pb)</td>
<td>99.8</td>
<td>2.59</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Event Generation II

• SM background events generated with MadGraph (v3.95). For $|\eta_{\text{jet}}|<2.5$, $\Delta R_{jj}>0.4$, $P_T^{\text{jet}}>20\text{GeV}$, the cross-sections are:
  - $pp \rightarrow w^+w^-bb\sim \sigma \sim 612\ \text{pb}$
  - $pp \rightarrow w^+w^-jj\ (j=u,d,s,c) \sim \sigma \sim 24\ \text{pb}$
  (Backgrounds with same-charge Ws negligible: $\sigma<1\text{pb}$.)

• All ntuples produced with ATLAS fast simulation ATLfast interfaced to Pythia in ATLAS framework, Athena release 11.0.4.1.

• CTEQ6L1 set of pdfs used.
Event Reconstruction

- Reconstruct one leptonic $W$:
  - Require exactly one lepton. $P_T > 15$ GeV
  - Use missing $E_T$ to reconstruct neutrino.

- Reconstruct one hadronic $W$:
  - Take 3rd and 4th most-energetic jets
  - Reject if $m_{jj} > 200$ GeV.
Event Reconstruction II

- Reconstruct $q_4$:
  - Use two most-energetic jets. $P_T > 30$ GeV
  - Combine each with either leptonic or hadronic $W$.
  - Ambiguity resolved by requiring minimum difference between two reconstructed-$q_4$ masses:

$$\Delta m_{jW} = m_{q_4}^1 - m_{q_4}^2$$

Require $\Delta m_{jW} < 100$ GeV
Background Rejection

- ATLfastB results for jet-tagging used. Reject if either of hard jets is b-tagged. ~40% reduction in background, with insignificant loss in signal.

- Scalar sum of all transverse momenta:

\[
H_T = \sum_{jet}^{4} P_T^{jet} + P_T^{lept} + P_T^{miss}
\]

- Reject events if \( H_T < H_T^{\text{min}} \) with \( H_T^{\text{min}} = 350 \text{ GeV} \) chosen for 250GeV signal.

- \( H_T^{\text{min}} \) can be increased for scans of higher-mass signals.
Results

With 1fb\(^{-1}\) of data:

- For \(m_{q_4} = 250\) GeV, a total of about \(50k\) events expected with \(S/B \approx 1.25\). (\(S/\sqrt{B} \approx 175\))
- For \(m_{q_4} = 500\) GeV, a total of about \(430\) events expected with \(S/B \approx 1.38\). (\(S/\sqrt{B} \approx 18.5\))
With $10\text{fb}^{-1}$ of data:

- For $m_{q4}=750\text{ GeV}$, a clear signal peak can be seen over the background.
- However, due to limited statistics of our $WWbb$ sample, there are other peaks in the final histogram.
Conclusions

- 4th family interactions modeled in CompHEP and signal and SM background Monte Carlo generated.
- First pass on the reconstruction and background rejection shows encouraging results for low-mid $m_{q4}$:
  - Top pair production will be the main background for 250 GeV, but even with very low integrated luminosity, thousands of events will be reconstructed, leaving way for further improvements.
  - For 500 GeV, the background is mostly flat continuum, but a clear peak observed with only 1fb$^{-1}$ of data.
- For the higher $m_{q4}$, to draw concrete conclusions more MC statistics for the SM background will be needed.
- No optimizations yet performed on any of the selection criteria.
Future Steps

• In the short term:
  – Generate larger background samples with higher $P_T$ hard jets.
  – Also look for background from $W+W$-jjj & $W+W$-bbj events.
  – Optimize selection criteria.
  – Explore smarter selection for hadronic $W$ jets.
  – Determine minimum integrated luminosity necessary for $3\sigma$ and $5\sigma$ observation, as a function of $q_4$ mass.

• In the longer term:
  – Explore reconstruction for events with both $W$s decaying leptonically.
  – Study how the signal would be distinguished from other models.
Backup Slides
Possible?

Precision EW data consistent with fourth generation (which has a heavy neutrino).

Example exclusion plot from Novikov, Okun, Rozanov, Vysotsky, PLB 529, 2002, for:

\[ M_{d4} = 200 \text{ GeV} \]
\[ M_{u4} = 220 \text{ GeV} \]
\[ M_{e4} = 100 \text{ GeV} \]
## Selection Efficiencies (%)

<table>
<thead>
<tr>
<th>Condition</th>
<th>sig@250</th>
<th>WWjj</th>
<th>WWbb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>34.5</td>
<td>30.9</td>
<td>36.3</td>
</tr>
<tr>
<td>4 jets</td>
<td>94.6</td>
<td>92.2</td>
<td>92.3</td>
</tr>
<tr>
<td>$P_T^{\text{lept}}&gt;15\text{GeV}$</td>
<td>91.3</td>
<td>90.3</td>
<td>89.8</td>
</tr>
<tr>
<td>$m_{jj}&lt;200\text{GeV}$</td>
<td>75.7</td>
<td>79.3</td>
<td>83.5</td>
</tr>
<tr>
<td>Hard jets tag $\neq b$</td>
<td>96.3</td>
<td>85.9</td>
<td>48.1</td>
</tr>
<tr>
<td>$P_T&gt;30\text{GeV}$</td>
<td>95.0</td>
<td>67.9</td>
<td>64.9</td>
</tr>
<tr>
<td>$h&gt;350\text{GeV}$</td>
<td>66.1</td>
<td>55.0</td>
<td>63.1</td>
</tr>
<tr>
<td>$\Delta m&lt;100\text{GeV}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>