Searches for vector-like quarks and Top-jet resonances with ATLAS

Merlin Davies
On behalf of the ATLAS collaboration

\[
\frac{g}{\sqrt{2}} W^+_{\mu} (\kappa_u D \bar{u}_R \gamma^\mu D_R + \kappa_d D \bar{d}_R \gamma^\mu U_R) + \frac{g}{2c_W} Z_{\mu} (\kappa_u U \bar{u}_R \gamma^\mu U_R + \kappa_d D \bar{d}_R \gamma^\mu D_R) + h.c.
\]
Overview

- I will present the results of 3 ATLAS searches performed with 2011 data.
- Vector-like quark (VLQ) searches (2)
  - Properties and theoretical motivations
  - Pair production of vector-like quark singlets (VLS) decaying by neutral current [arXiv:1204.1265]
    - $b' \rightarrow Zb$
    - $qq \rightarrow D q \rightarrow Wu q$ (CC channel)
    - $qq \rightarrow U q \rightarrow Zu q$ (NC channel)
- Top+jet resonance search (1)
  - Theoretical Motivation
  - Associated production of a top + jet resonance [ATLAS-CONF-2012-096]
    - $g q \rightarrow X \bar{t} \rightarrow t j \bar{t}$
General properties of vector-like quarks

- The *Left* and *Right* components of vector-like quarks (VLQ) transform identically under the weak force:
  - **Chiral:** $\sim W_\mu \bar{\psi} \gamma^\mu (1 - \gamma_5) \psi$  
  - **Vector:** $\sim W_\mu \bar{\psi} \gamma^\mu \psi$

- Important Phenomenological Properties of 4th generation *chiral* quarks:
  - Increases by a factor of $\sim 9$ the Higgs’ SM cross-section... We would have seen the Higgs long ago!
  - *Vacuum instability*: Their loop contributions to the Higgs’ propagator can render $\lambda$ negative!

$$V(\phi) = -\frac{1}{2} \mu^2 \phi^\dagger \phi + \frac{1}{4} \lambda (\phi^\dagger \phi)^2$$

- **VLQ evade** these problems because
  - They don’t have a Yukawa coupling to the Higgs
  - Contribute negligibly to the Higgs’ self-coupling

$t'$: chiral-fermion
Models predicting the existence of VLQs

- In many **BSM theories**, VLQ’s play the role of top-partners to cancel the top’s contribution to the Higgs’ self-coupling.

  - **Little Higgs (with T-Parity)**
    - Higgs arises naturally as a Pseudo-Goldstone Boson
    - Global SU(5) symmetry breaking at the weak scale ~TeV
  
  - **Composite Higgs, or strongly interacting Higgs**
    - A new strong force exists where the Higgs is composite
    - Other new composite states are phenomenologically identical to VLQ at energies below the energy scale of this new interaction → VLQ can interact with light quarks via this new strong force

- **Extra-dimension models**
  - Universal Extra Dimensions: Kaluza-Klein excitation of a chiral quark phenomenologically similar to a vector-like quark if the number of extra dimensions is odd.

- **GUT E6, SO(10), and others...**
  - Within many of the breaking schemes of these large groups, the final result contain a piece identical to the SM, and another containing, among other fermion fields, new up and down type vector-like quarks (E(6) only has down-type VLQ).
Vector-like quark search strategies

- Given the wide range of possible models predicting the existence of VLQ → We search for them while trying to stay as **model independent** as possible
- Although Vector-like quarks could exist as a series of singlets, doublets, and triplets, we chose to focus on 2 main possibilities which were the basis of 2 searches performed by ATLAS [arXiv:1204.1265, Phys.Lett. B712 (2012) 22-39]

1) A down-type vector-like quark singlet (VLS) coupling to 3\textsuperscript{rd} generation and produced in pair pp → \( b' \bar{b}' \rightarrow Zb \) (Zb,Wt, Hb)

![Diagram of b' decay](attachment://vector-like_diagram.png)

- The **probability** that at least one \( b' \) decays to \( Zb \) is parametrized by:
  \[
  \beta = 2 \times BR(b' \rightarrow Zb) - BR(b' \rightarrow Zb)^2
  \]
- In the limit of high \( b' \) mass
  \[
  BR(b' \rightarrow Wt) : BR(b' \rightarrow Hb) : BR(b' \rightarrow Zb) \rightarrow 2 : 1 : 1
  \]
- For \( b' \) masses in the range [200, 700] GeV, \( \beta \) varies from 0.9 to 0.5

No requirement on the decay of the second \( b' \)
Search for Vector-Like Quark Singlet (VLS) in Pair Production

- Experimental Analysis with 2.0 fb\(^{-1}\) of 2011 data
- Looking for \(Z(ee) + > 1\) b-jet events
- Electron cuts:
  - \(p_T > 25\) GeV
  - \(|\eta| < 2.47\) while removing \(1.37 < |\eta| < 1.52\)
  - \(|m_{ee} - m_Z| < 15\) GeV
- Jet cuts:
  - anti-\(k_T\) algorithm cone \(R = 0.4\)
  - At least 75% of the total track \(p_T\) point the selected vertex
  - \(|\eta| < 2.5\)
  - \(p_T > 25\) GeV
  - Require at least one \(b\)-tagged event
    - 60% efficiency for \(b\)-hadrons
    - measured in \(t\bar{t}\) events
  - Rejection rate of 300 for light flavour jets

MC Generators Used:
- \(Z+jets \rightarrow AlgGen\) (scaled to NNLO[3])
  → Sherpa used as cross check
- \(t\bar{t} \rightarrow MC@NLO (NNLO \sigma\) comp. using HATHOR[6])

\[Z(ee) + \geq 1\ b\text{-jet}\]
Signal Region for VLS

- Since we have **back-to-back** $b'$, we place a cut
  - $p_T(Zb) > 150$ GeV
- Signals generated by MADGRAPH with the G4LHC extension
- Signal cross-sections vary from 80 $\mu$b to 30 $fb$ in the range $m_{b'} = [200, 700]$ GeV
Results - Down-Type VLS Search

- Important systematics:
  - Renormalization and factorization scale (14%)
  - AlpGen vs Sherpa shape differences (12%)
  - b-tagging efficiency (12%)

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<tr>
<th>Source</th>
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<tbody>
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<td>Z+light</td>
<td>19 ± 7</td>
</tr>
<tr>
<td>Z+charm</td>
<td>18 ± 7</td>
</tr>
<tr>
<td>Z+bottom</td>
<td>52 ± 17</td>
</tr>
<tr>
<td>ttbar</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>Other SM</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td>Total SM</td>
<td>110 ± 30</td>
</tr>
<tr>
<td>DATA</td>
<td>100</td>
</tr>
<tr>
<td>mb' = 350 GeV</td>
<td>55 ± 7</td>
</tr>
<tr>
<td>mb' = 450 GeV</td>
<td>14 ± 2</td>
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Results - Down-Type VLS Search

- Since no excess is found, we computed limits based on the $CL_s$ modified frequentist approach.
- Assuming VLS mixing solely to 3rd generation quarks and
  - $\beta = 1$, we find
    - $m_{b'} < 400$ GeV at 95% C.L.
  - $\beta = 0.63$, we find
    - $m_{b'} < 358$ GeV at 95% C.L.
2) **VLQ** are generally expected to couple to 3\textsuperscript{rd} generation, but under some symmetries → it is possible to construct models with VLQ coupling primarily to light quarks.

- **One such model it to have a pair of VLQ doublets** [arXiv:0806.396]

  \[
  \begin{pmatrix}
  U \\
  D
  \end{pmatrix}, \begin{pmatrix}
  X \\
  Y
  \end{pmatrix} \quad Q_U = \frac{2}{3}, \quad Q_D = -\frac{1}{3}, \quad Q_X = -\frac{5}{3} \quad \text{and} \quad Q_Y = \frac{4}{3}
  \]

- If the mass of these VLQ doublets are *almost* degenerate, cancellations can occur between the mixing and coupling of VLQs to light quarks.

- **A model independent Lagrangian can be written (focusing on U, D)**:

  \[
  \frac{g}{\sqrt{2}} W^+_\mu \left( \kappa_{uD} \bar{u}_R \gamma^\mu D_R + \kappa_{dD} \bar{d}_R \gamma^\mu U_R \right) + \frac{g}{2c_W} Z_\mu \left( \kappa_u \bar{u}_R \gamma^\mu U_R + \kappa_{dD} \bar{d}_R \gamma^\mu D_R \right) + h.c.
  \]

  - where the couplings

    \[
    \kappa_{qQ} = \frac{v}{m_Q} \tilde{\kappa}_{qQ}
    \]

  - In this degenerate VLQ doublet model, only mild EW constraints persists, in fact

    \[
    \tilde{\kappa}_{qQ} \sim 1
    \]
Vector-like quark search strategies (Cont.)

- Since the coupling $\tilde{\kappa}_{qQ}$ can be order $\sim 1$

- Single production is a more powerful channel for this search than pair production $\rightarrow$ it is kinematically more favourable.
Search for VLQ coupling to light generations in single production

- Experimental Analysis with \(1.04 \text{ fb}^{-1}\) of 2011 data
- Looking for \(W/Z + 1\) high \(p_T\) jet + 1 forward jet
- Basic Electron/Muon cuts
  - \(p_T > 25\) GeV
  - Isolated within a cone of \(\Delta R = 0.2\)
- Basic Jet cuts
  - anti-\(k_t\) algorithm cone \(R = 0.4\)
  - Remove jets within \(\Delta R = 0.5\) with an electron
  - \(|\eta| < 4.5\)
  - \(p_T > 25\) GeV

**MC Generators Used:**
- \(W/Z+\text{jets} \rightarrow \text{AlgGen (scaled to NNLO)}[3]\)
- \(tt / \text{single top} / \text{Di-bosons} \rightarrow \text{MC@NLO}\)
VLQ Signal Extraction - Signal Region

- **CC channel**
  - Missing $E_T > 50$ GeV (reduce Multi-jet background)
  - Leading Jet $p_T > 50$ GeV
  - $N$ jets $\geq 2$
  - $\Delta\eta$(leading jet, forward jet) $> 1.0$
  - $m_T(W) > 40$ GeV
  - $\Delta\phi$(lepton, $\nu$) $< 2.4$ rad
  - Get Missing $p_z$ solution for $\nu$ from $m(W)$ equation

- **NC Channel**
  - $|m_\nu - m_Z| < 25$ GeV
  - $p_T(Z) > 50$ GeV
  - $\Delta\eta$(leading jet, forward jet) $> 1.0$
  - Leading Jet $p_T > 50$ GeV

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ATLAS Experiment

ICHEP 2012  Merlin Davies  Melbourne July 6th
Results - VLQ NC channel

- Due to a mis-modelling of the Z+jets background, a linear correction (--- in histogram above) is applied.
- We fitted the ratio Data/MC while excluding the range $[m_U - 200, m_U + 100]$ GeV around each tested signal mass.
- Main systematics:
  - Linear fit correction uncertainty
  - Renormalization/Factorization Scales (4% to 12% depending on signal mass)
  - JES (20% on normalization and 5% on efficiency) (more sensitive to shape than normalization uncertainties)

### Source

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<tbody>
<tr>
<td>Z+jets</td>
<td>8600 ± 830</td>
</tr>
<tr>
<td>ttbar</td>
<td>148 ± 13</td>
</tr>
<tr>
<td>Dibosons</td>
<td>96 ± 11</td>
</tr>
<tr>
<td><strong>Total SM</strong></td>
<td><strong>8850 ± 67</strong></td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td><strong>8175</strong></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>m_U</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>531 ± 31</td>
</tr>
<tr>
<td>600</td>
<td>38 ± 6</td>
</tr>
<tr>
<td>1000</td>
<td>4.6 ± 2.1</td>
</tr>
</tbody>
</table>
**Results - VLQ CC channel**

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal Region Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>31100 ± 6600</td>
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<tr>
<td>ttbar</td>
<td>4890 ± 400</td>
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<tr>
<td>Single Top</td>
<td>1440 ± 20</td>
</tr>
<tr>
<td>Multijet</td>
<td>1010 ± 50</td>
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<tr>
<td>Z+jets</td>
<td>560 ± 200</td>
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<tr>
<td>Dibosons</td>
<td>372 ± 84</td>
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<tr>
<td><strong>Total SM</strong></td>
<td><strong>39400 ± 6700</strong></td>
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<tr>
<td>DATA</td>
<td>37970</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>m_D (GeV)</th>
<th>Yield (Events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>266 ± 22</td>
</tr>
<tr>
<td>1000</td>
<td>28 ± 6</td>
</tr>
</tbody>
</table>

- **Same linear fit correction** method as in the NC is used here (--- in histogram above).
- **Multijet Background**: Use the missing $E_T$ distribution between [10, 30] GeV and extract a data-driven template after subtracting all non-multijet contributions.
- **Main Systematics**: same as for the NC, but with additional uncertainties associated the multijet background estimation.
• Once again, no excess is found, we hence compute limits based on the CL$_{s}$ method

• Assuming a coupling of

\[ \tilde{\kappa}_{qQ} = 1 \]

We obtain the limits:

\[ m_U < 760 \text{ (820) GeV at 95\% C.L.} \]

\[ m_D < 900 \text{ (840) GeV at 95\% C.L.} \]
Search for Top-jet Resonances

• One of the few discrepancies between SM expectations and observation is the forward-backward asymmetry measurements from the Tevatron [arXiv:1101.0034, arXiv:1107.4995]

• Possible explanation: Top-flavour violating processes

• Look for a new heavy resonance $X \rightarrow tj(\bar{t}j)$ produced in association with a top-quark (decaying to jets)

\[ t \rightarrow W(l\nu) + b \]
\[ \bar{t} \rightarrow W(jj) + b \]

• Two types of $X$ resonances were considered
  • color singlet $W' \rightarrow m(antitop+jet)$ resonance
  • di-quark color triplet $\rightarrow m(top+jet)$ resonance

• Assume these resonances have unit right-handed coupling to $tq$

• The $X$ resonance occurs in the $m(top+jet)$ or $m(antitop+jet)$ channel, but not in both! (important during limit setting)
Control and Signal Region definitions

W+jet C.R.

- **Standard Cuts:**
  - Find events with exactly 1 lepton \((E_T(\text{el}) > 25 \text{ GeV}, p_T(\mu) > 20 \text{ GeV})\)
  - \(m_T(W) > 30 \text{ GeV}\) (electron channel)
  - \(m_T(W) + \text{Missing } E_T > 60 \text{ GeV}\) (muon channel)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>W+jets CR</th>
<th>ttbar CR</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td># Jets</td>
<td>(\geq 5)</td>
<td>4 + (\geq 1) soft</td>
<td>(\geq 5)</td>
</tr>
<tr>
<td># b-tagged Jets</td>
<td>0</td>
<td>(\geq 1)</td>
<td>(\geq 1)</td>
</tr>
</tbody>
</table>
• Expected and Observed distributions of the **top+jet mass spectrum** with **4.7 fb^-1** of 2011 data

• Signals shown assume unit coupling \( g_R \) to the new resonance

• Main systematic contributors:
  • JES (10% on background, 21% on signal)
  • b-tagging efficiency (16%)
**Limits on Top-jet Resonances**

- Since no excess is observed, we computed limits on the color singlet $W'$ and color triplet models ($CL_s$ method) while looking at a specific region in the $m_{tj} - m_{\bar{t}j}$ plane.

- **With $g_R = 1$**
  - $m_{W'} < 350$ ($450$) GeV at 95% C.L. (singlet)
  - $m_{di-quark} < 430$ ($700$) GeV at 95% C.L. (triplet)
In terms of the coupling $g_R$

- The previous limits can be re-expressed in terms of $g_R$
- Assumes cross-sections scales as $g_R^2$
Summary

• Two ATLAS searches for VLQ have been performed:
  • Pair production of a VLS: \( b' \to Z(\ell\ell)b \)
    • \( m_{VLS} < 400 \text{ GeV at 95\% C.L.} \)
  • Single production of a VLQ doublet coupling to light quarks:
    • \( qq \to D \, q \to Wd \, q \)
      • \( m_{D-\text{type}} < 900 \ (840) \text{ GeV at 95\% C.L.} \)
    • \( qq \to U \, q \to Zu \, q \)
      • \( m_{U-\text{type}} < 760 \ (820) \text{ GeV at 95\% C.L.} \)

• One ATLAS search for Top+jet resonance
  • \( g \, q \to X \, t \to \bar{t}j \, t \)
    • \( m_{W'} < 350 \ (450) \text{ GeV at 95\% C.L.} \ (\text{singlet}) \)
    • \( m_{\text{di-quark}} < 430 \ (700) \text{ GeV at 95\% C.L.} \ (\text{triplet}) \)

• Stay tuned for results with the full 2011/2012 datasets
Thank You!