Search for vector like quarks with ATLAS

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Vector-Like Quarks - What and Why?

Colored, spin-½ particles ⇒ “Quarks”
Both chiralities transform the same under SM gauge groups ⇒ “Vector-like”
- Avoids constraints from Higgs measurements

Higgs mass is quadratically divergent in the SM, but this can be naturally cancelled by VLQs
- As a result, VLQs show up in many BSM models (Little/Composite Higgs, Topcolor, GUTs, …)
- But naturalness requires VLQ mass ~TeV (Accessible at the LHC!)

Couple to SM through mixing with SM quarks
- Naturalness + FCNC constraints imply mixing with 3rd generation

<table>
<thead>
<tr>
<th>Q[ϵ]</th>
<th>singlets</th>
<th>VLQs doublets</th>
<th>triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/3</td>
<td>(T)</td>
<td>(X T)</td>
<td>(X T)</td>
</tr>
<tr>
<td>2/3</td>
<td>(B)</td>
<td>(T B)</td>
<td>(T B)</td>
</tr>
<tr>
<td>-1/3</td>
<td></td>
<td>(B Y)</td>
<td>(T B)</td>
</tr>
<tr>
<td>-4/3</td>
<td></td>
<td>(Y B)</td>
<td>(B Y)</td>
</tr>
</tbody>
</table>

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What do we look for?

Pair Production via QCD
• Depends only on mass
⇒ ~Model-independent

Decays dictated by quantum numbers:
\[ T \rightarrow W_b, Z_t, H_t \]
\[ B \rightarrow W_t, Z_b, H_b \]
⇒ Rich phenomenology!

Branching ratios are model-dependent
• Constrained in some scenarios
  ➢ “Singlet” scenario
  ➢ “Doublet” scenario
    (assuming mixing only in up sector)
• But best to test all possibilities!

Single production via EW boson
• Depends on mass and coupling

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Pair Production: General Strategy

Set limits as a function of the branching ratios:

Perform multiple analyses to target different decays:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>( T\bar{T} ) decay</th>
<th>( B\bar{B} ) decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H(bb)t + X )</td>
<td>( HtH\bar{t} )</td>
<td>-</td>
</tr>
<tr>
<td>( W(\ell\nu)b + X )</td>
<td>( WbW\bar{b} )</td>
<td>-</td>
</tr>
<tr>
<td>( W(\ell\nu)t + X )</td>
<td>-</td>
<td>( WtW\bar{t} )</td>
</tr>
<tr>
<td>( Z(\nu\nu)t + X )</td>
<td>( ZtZ\bar{t} )</td>
<td>-</td>
</tr>
<tr>
<td>( Z(\ell\ell)t/b + X )</td>
<td>( ZtZ\bar{t} )</td>
<td>( ZbZ\bar{b} )</td>
</tr>
<tr>
<td>Tril./s.s. dilepton</td>
<td>( HtH\bar{t} )</td>
<td>( WtW\bar{t} )</td>
</tr>
<tr>
<td>Fully hadronic</td>
<td>( HtH\bar{t} )</td>
<td>( HbH\bar{b} )</td>
</tr>
</tbody>
</table>

Our goal: maximize sensitivity in full triangle
$Wb + X$

Pre-fit

$T \rightarrow WbWb$

$m_T = 1.2 \text{ TeV}$

Pre-fit

$\ell b + X$

$\ell \rightarrow WbWb$

$m_T = 1.2 \text{ TeV}$

Pre-fit

$\ell + m_T = 1.2\text{ TeV}$

Pre-fit

$\ell + m_T = 1.2\text{ TeV}$
$Wb+X$

**Post-fit**

$TT \rightarrow WbWb$

$m_T = 1.2 \text{ TeV}$

**SR Post-fit**

**CR Post-fit**

$\sqrt{s} = 13 \text{ TeV}$, 36.1 fb$^{-1}$

**ATLAS Simulation**

$\mathcal{B}(B \rightarrow Wt) = 1$

![Graph showing data and predictions for different processes in ATLAS](image)
$Wb+X$

$\ell T \rightarrow Wb+X$ 1-lepton
SU(2) singlet

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

**Post-fit**

**TT → Wb+X 1-lepton**

SU(2) singlet

SU(2) doublet

Observed 95% CL mass limit [GeV]

500 600 700 800 900 1000 1100 1200 1300 1400

\( \mathcal{B}(T \rightarrow Wb) \)

\( \mathcal{B}(T \rightarrow Ht) \)

\( \mathcal{B}(T \rightarrow Wb) \)

\( \mathcal{B}(T \rightarrow Ht) \)

\( \mathcal{B}(T \rightarrow Wb) \)

\( \mathcal{B}(T \rightarrow Ht) \)

\( \mathcal{B}(T \rightarrow Wb) \)

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\( \mathcal{B}(T \rightarrow Ht) \)

\( \mathcal{B}(T \rightarrow Wb) \)

\( \mathcal{B}(T \rightarrow Ht) \)
$Ht+X$

Split into 34 search regions based on:

- # leptons
- # small-R jets
- # b-tags
- # large-R jets

**Jet multiplicity**

- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14

**Fraction of Events**

- 0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1

**Preselection**

- $\sqrt{s}=13$ TeV, 13.2 fb$^{-1}$

**Simulation Preliminary**

- ATLAS

**Total background**

- $TtT$ (1 TeV)
- $TtT$ singlet (1 TeV)
- $tZtZ\rightarrow TtT$ (1 TeV)

**$Ht+X$**

- $t\bar{t}$ doublet (1 TeV)
- $t\bar{t}$ singlet (1 TeV)
- $t\bar{t}H$ (1 TeV)

**Mass-tagged jet multiplicity**

- 0
- 1
- 2
- 3
- 4

**$Ht+X$**

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1

**$Ht+X$**

- 0
- 1
- 2
- 3
- 4
- 5
**Ht+X**

Split into 34 search regions based on:

- # leptons
- # small-R jets
- # b-tags
- # large-R jets

Most sensitive search regions:

<table>
<thead>
<tr>
<th>Search Region</th>
<th>Data / Bkg</th>
<th>Events / 600 GeV</th>
<th>Events / 1000 GeV</th>
<th>Events / 400 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td></td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>1t, 1H, ≥7j, 3b, HM</td>
<td>Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre-fit</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*JHEP 07 (2018) 089*
Split into 34 search regions based on:
- # leptons
- # small-R jets
- # b-tags
- # large-R jets

Most sensitive search regions:

\[ 1000 \text{ GeV} \leq m_{T} \leq 1500 \text{ GeV} \]
\[ 1500 \text{ GeV} \leq m_{T} \leq 2000 \text{ GeV} \]
\[ 2000 \text{ GeV} \leq m_{T} \leq 2500 \text{ GeV} \]
\[ 2500 \text{ GeV} \leq m_{T} \leq 3000 \text{ GeV} \]
\[ 3000 \text{ GeV} \leq m_{T} \leq 3500 \text{ GeV} \]

Data / Bkg

95% CL mass limit \[ \text{ [GeV] } \]

ATLAS
\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
1-lepton + 0-lepton combination
Observed limit

SU(2) doublet
SU(2) singlet

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Cut-and-count analysis

- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit $t\bar{t}$ and $W+$jets normalizations
- Validation Regions – To check modeling of backgrounds

### Region | SR
--- | ---
Observed events | 7
Fitted bkg events | $6.1 \pm 1.9$
Fitted $t\bar{t}$ events | $2.5 \pm 1.7$
Fitted $W+$jets events | $1.1 \pm 0.7$
Fitted singletop events | $1.1 \pm 0.7$
Fitted $t\bar{t}+V$ events | $0.91 \pm 0.20$
Fitted diboson events | $0.6 \pm 0.6$
MC exp. bkg events | 6.5
Singlet (Doublet) $T$ w/ $m=1$ TeV | $5 \ (10)$
Cut-and-count analysis

- **Signal Region (Bin)** - Kinematic cuts to optimize VLQ sensitivity
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- **Validation Regions** - To check modeling of backgrounds

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**Table:**

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<tr>
<th>Region</th>
<th>Observed Events</th>
<th>Fitted bkg Events</th>
<th>Fitted $t\bar{t}$ Events</th>
<th>Fitted $W+$jets Events</th>
<th>Fitted singletop Events</th>
<th>Fitted $t\bar{t}+V$ Events</th>
<th>Fitted diboson Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>7</td>
<td>$6.1 \pm 1.9$</td>
<td>$2.5 \pm 1.7$</td>
<td>$1.1 \pm 0.7$</td>
<td>$1.1 \pm 0.7$</td>
<td>$0.91 \pm 0.20$</td>
<td>$0.6 \pm 0.6$</td>
</tr>
<tr>
<td>TVR</td>
<td>$7 \pm 10$</td>
<td>$6.5$</td>
<td>$4.6 \pm 2.5$</td>
<td>$3.4 \pm 1.8$</td>
<td>$3.3 \pm 1.7$</td>
<td>$2.9 \pm 1.5$</td>
<td>$2.5 \pm 1.4$</td>
</tr>
</tbody>
</table>

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**Graph:**

- ATLAS
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

**Observed 95% CL mass limit [GeV]:**

- Singlet (Doublet)
- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $Zt+X$ 1l+$E_T^{miss}$
- SU(2) singlet
- SU(2) doublet

---

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

**Legend:**

- **ATLAS**
- SU(2) singlet
- SU(2) doublet

---

**ATLAS Experiment**

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ATLAS
\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
1-lepton + 0-lepton combination
Observed limit

SU(2) doublet
SU(2) singlet

\(\mathbb{B}(T \to Wb)\)
\(\mathbb{B}(T \to Ht)\)

Observed 95\% CL mass limit [GeV]

ATLAS
\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)
1-lepton + 0-lepton combination
Observed limit

SU(2) doublet
SU(2) singlet

\(\mathbb{B}(T \to Wb)\)
\(\mathbb{B}(T \to Ht)\)
Combination!
Pair Production: Combination

Perform a statistical combination of all pair-production searches for both $TT$ and $BB$ production

$\Rightarrow m_T < 1.3$ TeV excluded for all Branching Ratios*

$\Rightarrow m_B < 1.0$ TeV excluded for all Branching Ratios*

*Assuming it decays only to SM particles
Single Production

- Depends on couplings to SM quarks

- But could be the dominant production process for high VLQ masses

\[ q \rightarrow Wb \quad \text{or} \quad Wb \rightarrow q' \]

J.A. Aguilar-Saavedra et al., PRD 88, 094010 (2013)
Single Production: T/Y → Wb

Perform fit to $m_{VLQ}$ in signal region and two control regions
Single Production: $T/Y \rightarrow Wb$

Perform fit to $m_{VLQ}$ in signal region and two control regions

Signal prediction can have significant interference effects!
Single Production: $T/Y \rightarrow Wb$

Perform fit to $m_{VLQ}$ in signal region and two control regions.

Signal prediction can have significant interference effects!

Iterative approach to determine coupling limit:
1. Pick coupling and make “signal” template
2. Set limit on “cross section”
3. Determine coupling corresponding to that cross section
Perform fit to $m_{VLQ}$ in signal region and two control regions

Signal prediction can have significant interference effects!

Iterative approach to determine coupling limit:
1. Pick coupling and make “signal” template
2. Set limit on “cross section”
3. Determine coupling corresponding to that cross section

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Single Production

Z_{ℓℓ}+t analysis: Limits on $T$

$ℓ^±ℓ^±/3ℓ+b$ analysis: Limits on $X^{5/3}$

$H_{γγ}+b$ analysis: Limits on $B$
Conclusions

- ATLAS has a broad VLQ program searching for pair and single-production.

- VLQs can provide a natural solution to the hierarchy problem... if they are not too heavy.

- So far, data appear to agree with SM:
  - Combination of pair-production analyses:
    - $m_T > 1.3$ TeV
    - $m_B > 1.0$ TeV
  - (Similar limits from CMS searches)
Conclusions

• ATLAS has a broad VLQ program searching for pair and single-production

• VLQs can provide a natural solution to the hierarchy problem
  … if they are not too heavy

• So far, data appear to agree with SM
  ➢ Combination of pair-production analyses:
    ✷ $m_T > 1.3$ TeV
    ✷ $m_B > 1.0$ TeV
    (Similar limits from CMS searches)

• If VLQs solve the hierarchy problem, they are starting to feel the heat...
  … and we have 100/fb more data in the analysis pipeline!

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Thank you

And special thanks to:

DOE for supporting this research

To the ATLAS Collaboration

• Complete list of ATLAS exotic results: 
  twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Run 2 Data

Results presented today use data from 2015-2016 (~36/fb)
In the process of analyzing full Run 2 data set (~136/fb)

⇒ Thank you to LHC Operations!
Beyond $B(T \to Wb + Zt + Ht) = 1$ Assumption

- In the triangular BR plots we assume that VLQs only decay to SM particles
- This is not the case in most of the composite Higgs models (e.g. arXiv:1704.07388)

→ A non-negligible decay to a non-SM particle (e.g. the new scalar $S$) can significantly change the limits in the BR plane

[arXiv:1705.03013]
Beyond $B(T \rightarrow Wb+Zt+Ht) = 1$ Assumption

- Depending on the model $S$ can be $\sim$ stable, evading detection, or decay e.g. to $bb$, $tt$, $HH$

- Ideally we would have dedicated searches for these channels

- Some of our current searches might even be (partially) sensitive to $S$, depending on its decay modes
  - We might even be able to tailor our analysis to increase the sensitivity to these additional final states

- Nonetheless, providing the BR plane limits for relaxed $\Sigma(BR)$ assumptions gives a conservative hint on the impact of $S$ (i.e. gives us the maximum effect in the degradation of our results)
  - As long as we provide enough information and are very clear about the assumptions, this would fit well as a complementary result for our papers (in particular the combination one)
Beyond $B(T\rightarrow Wb + Zt + Ht) = 1$ Assumption

- Another recent proposal: arXiv:1705.02526

one example:

\[ T \rightarrow H_0^0 t, \quad T \rightarrow P_0^0 t, \quad T \rightarrow H^0 b, \]
Branching Ratios

Aguilar-Saavedra et al., PRD 88, 094010 (2013)

Branching Ratio vs. $m_T$ [GeV]

- SU(2) Singlet
- (X,T) Doublet
- $T \rightarrow Wb$
- $T \rightarrow Zt$
- $T \rightarrow Ht$

$F_{33}$
Heavy Objects

1) Large-R jets from calorimeter cells
   - R=1.0, C/A, trimmed jets
   - Dedicated calibrations and uncertainties
   - Use sub-structure to tag W bosons

2) Large-R “re-clustered” jets
   - Small-R jets are the input to R=1.0 clustering
   - Inherit calibration and uncertainties
   - Cut on large-R jet mass to “tag”
Zt+X: Strategy

Cut-and-count analysis

- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit $t\bar{t}$ and $W$+jets normalizations
- Validation Regions – To check modeling of backgrounds

With one $W$ ➞ $\ell\nu$

**Signal Region (Bin)**
- Kinematic cuts to optimize VLQ sensitivity

**Control Regions**
- To fit $t\bar{t}$ and $W$+jets normalizations

**Validation Regions**
- To check modeling of backgrounds

- 4 small-$R$ jets
- ≥ 1 b-tagged

**Missing Energy**

- 1 Lepton
- 2 large-$R$ jets

$E_T^{miss}$
Zt+X: Validation Regions

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

**Modeling looks good!**

Do we see any excess in the Signal Region?

**Data/Pred.**

Events / 50 GeV

\( E_{\text{miss}} \) [GeV]

300 350 400 450 500 550 600

0 10 20 30 40 50 60

**Events / 50 GeV**

\( m_{t\bar{t}} \) [GeV]

100 150 200 250 300 350 400 450 500 550 600

0 10 20 30 40 50 60

**Events / 25 GeV**

\( T_{2}^{\text{am}} \) [GeV]

100 110 120 130 140 150 160 170 180 190 200

0 5 10 15 20 25 30 35 40 45 50 55 60

**Events / 50 GeV**

\( T_{2}^{\text{am}} \) [GeV]

200 250 300 350 400 450 500 550 600

0 10 20 30 40 50 60

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Zt+X: Signal Region

<table>
<thead>
<tr>
<th>Region</th>
<th>SR</th>
<th>TCR</th>
<th>WCR</th>
<th>TVR</th>
<th>WVR</th>
<th>STVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>7</td>
<td>437</td>
<td>303</td>
<td>112</td>
<td>131</td>
<td>143</td>
</tr>
<tr>
<td>Fitted bkg events</td>
<td>6.1±1.9</td>
<td>437±21</td>
<td>303±17</td>
<td>109±35</td>
<td>127±31</td>
<td>125±27</td>
</tr>
<tr>
<td>Fitted $t\bar{t}$ events</td>
<td>2.5±1.7</td>
<td>280±40</td>
<td>38±15</td>
<td>90±40</td>
<td>15±8</td>
<td>53±23</td>
</tr>
<tr>
<td>Fitted $W + \text{jets}$ events</td>
<td>1.1±0.7</td>
<td>70±28</td>
<td>224±27</td>
<td>3.5±2.0</td>
<td>77±30</td>
<td>15±7</td>
</tr>
<tr>
<td>Fitted singletop events</td>
<td>1.1±0.7</td>
<td>63±24</td>
<td>10±5</td>
<td>4.2±2.6</td>
<td>3.3±3.5</td>
<td>46±17</td>
</tr>
<tr>
<td>Fitted $t\bar{t} + V$ events</td>
<td>0.91±0.20</td>
<td>9.7±1.6</td>
<td>1.03±0.30</td>
<td>7.0±1.4</td>
<td>1.9±0.7</td>
<td>8.3±1.4</td>
</tr>
<tr>
<td>Fitted diboson events</td>
<td>0.6±0.6</td>
<td>11±5</td>
<td>30±12</td>
<td>1.3±1.3</td>
<td>31±9</td>
<td>1.7±1.1</td>
</tr>
<tr>
<td>MC exp. bkg events</td>
<td>6.5</td>
<td>450</td>
<td>398</td>
<td>106</td>
<td>160</td>
<td>129</td>
</tr>
</tbody>
</table>

Singlet (Doublet) $T$ w/ $m=1$ TeV 5 (10)

⇒ Also consistent with SM 😞
Run 1 Limits on TT
Simple Overlay of Analyses

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Exp. exclusion
- Obs. exclusion

- Blue: \( W(b\nu)b+X \) [arXiv:1707.03347]
- Green: \( H(bb)t+X \) [arXiv:1803.09678]
- Red: \( Z(\nu\nu)t+X \) [arXiv:1705.10751]
- Black: All-had

\( m_T \) values:
- \( m_T = 800 \text{ GeV} \)
- \( m_T = 950 \text{ GeV} \)
- \( m_T = 1000 \text{ GeV} \)
- \( m_T = 1050 \text{ GeV} \)
- \( m_T = 1100 \text{ GeV} \)
- \( m_T = 1150 \text{ GeV} \)
- \( m_T = 1200 \text{ GeV} \)
- \( m_T = 1300 \text{ GeV} \)
- \( m_T = 1400 \text{ GeV} \)

Exclude all branching ratios for \( m_T < 1.1 \text{ TeV} \)

Combination of Analyses

Exclude all branching ratios for $m_T < 1.3$ TeV

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

VLQ Combination

Combination of Analyses

Exclude all branching ratios for $m_T < 1.3$ TeV

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