Search for Vector-Like Quarks with the ATLAS Detector

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On Behalf of the ATLAS Collaboration
Vector-like quarks (VLQ): predicted by many new physics models aimed at solving hierarchy problem (Composite Higgs, Little Higgs...).

- **“Vector-like”:** left- and right-handed components have the same quantum numbers.
- **“Quarks”:** spin-$\frac{1}{2}$ fermions.

VLQs couple to Standard Model particles.

- They can arise in multiplets.
- ATLAS searches focus on singlets or doublets, and on $T^{+2/3}$ and $B^{-1/3}$.

\[
T_{L,R}^0, \quad B_{L,R}^0, \quad (X T^0)_{L,R}, \quad (T^0 B^0)_{L,R}, \quad (B^0 Y)_{L,R}, \quad (X T^0 B^0)_{L,R}, \quad (T^0 B^0 Y)_{L,R}
\]

(singlets), (doublets), (triplets).
VLQs can be produced **in pairs** or **singly**.

- **Pair**: Model independence.
- **Single**: Higher cross section at high mass.

For these searches, we assume:
- VLQs couple only to SM particles.
- VLQs decay always to a boson ($W,Z,H$) and $3^{\text{rd}}$ generation quark ($t,b$).

![Maximum Cross-Sections](image)

**arXiv:1306.0572**
Pair-Produced VLQs

Strategy for pair-production is to target different final states with optimized analyses. Pair searches are relatively model independent.

All searches use 36 fb⁻¹ of 13 TeV ATLAS data, taken in 2015-2016.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT→H(→bb)t + X</td>
<td>CERN-EP-2018-031</td>
</tr>
<tr>
<td>TT→W(→lν)b + X</td>
<td>JHEP 10 (2017) 141</td>
</tr>
<tr>
<td>TT→Z(→νν)t + X</td>
<td>JHEP08(2017)052</td>
</tr>
<tr>
<td>(TT/BB) Trilepton/</td>
<td></td>
</tr>
<tr>
<td>Same-sign dilepton</td>
<td></td>
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<tr>
<td>(TT/BB) Fully-hadronic</td>
<td></td>
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</tbody>
</table>

Combination of all-above: ATLAS-CONF-2018-032

*Charge conjugation is implied here and elsewhere.
**TT/BB→Zt/b+X**

**Goal:** Target decays with at least 2 leptons consistent with Z boson decay.

**Pre-selection:**
- $\geq 2$ e/μ, with one pair consistent with Z decay
- $\geq 2$ jets and $\geq 1$ b-tagged jets

**Four signal regions defined:**
- **3 dilepton signal regions with**
  - $p_T^{ll} > 250$ GeV and $\geq 2$ b-tagged jets
- **0/1 large-radius calo jets with**
  - $H_T > 800$ GeV
- **2 large-radius calo jets with**
  - $H_T > 1150$ GeV
- **1 trilepton signal region (≥ 3 e/μ) with**
  - $p_T^{ll} > 200$ GeV and $\geq 1$ b-tagged jets

**Final Discriminants:** $H_T$, $m_{Zb}$, and $S_T$
**TT/BB\(\rightarrow\)Zt/b+X (2)**

**Backgrounds:** Backgrounds from simulation, corrected in fit using control regions for:

- Top quark pairs
- Z+jets
- Top quark pairs + X
- Diboson

![Graphs showing data and backgrounds](image)
Fully-Hadronic VLQ

**Goal:** Target all decay modes of T/B with 0 leptons.

**Selection:**
- 0 e/μ & \( \geq 4 \) high-\( p_T \) R=0.4 jets
- \( \geq 2 \) b-tagged jets
- 40 GeV < \( E_T^{\text{miss}} \) < 200 GeV
- \( H_T > 1250 \) GeV
- \( \geq 2 \) high-\( p_T \) variable-radius reclustered (vRC) jets
  - Good for busy final states!

\( vRC \) jets are tagged as \( V, H, \) or top, based on a multi-class DNN-tagger.

\( V-, H-, t-, \) and \( b \)-tagged multiplicity defines the 12 signal regions above.
Fully-Hadronic VLQ (2)

Multi-jet Backgrounds: “ABCD” method
- $N_C N_B / N_A$, calculated bin-by-bin.

Top Backgrounds: Simulation
- Floating normalization in the final fit of background to data.

Final Discriminant: “Signal LLH”
- Summed matrix element calculation of VLQ signal likelihood.

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- $N_C N_B / N_A$, calculated bin-by-bin.

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**Final Discriminant: “Signal LLH”**

- Summed matrix element calculation of VLQ signal likelihood.

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

VLQ All-hadronic
(HH,0t,3b)

Separation: 20.1%
Trilepton/Same-sign Dilepton VLQ

Goal: Target all \( \geq 2 \) e/\( \mu \) decay modes of T/B

Selection: 8 1-bin signal regions with selections on \( H_T \), \( E_{T\text{miss}} \), \( n_{\text{leptons}} \) and \( n_{b\text{-jets}} \)

Data-driven Backgrounds:
- Fake/non-prompt e/\( \mu \) backgrounds estimated using a matrix method
- Charge mis-ID backgrounds (for same-sign dilepton events) estimated via rate measured in data.
VLQ Combination

All 13 TeV pair-production analyses with 36.1 fb$^{-1}$ are combined.

Significantly extends the reach of individual searches!

Excludes $m_{T(B)} < 1.31$ (1.03) TeV for any considered branching ratio!
Singly-Produced VLQ

13 TeV results in the search for single production include 2015, 2016, and 2017 data!

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lumi (fb$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T \rightarrow Wb$</td>
<td>3.2</td>
<td>ATLAS_CONF_2016_072</td>
</tr>
<tr>
<td>$T/B \rightarrow Z(t/b)$</td>
<td>36.1</td>
<td>CERN-EP-2018-145</td>
</tr>
<tr>
<td>$B \rightarrow H(\rightarrow \gamma\gamma)b$</td>
<td>79.8</td>
<td>ATLAS_CONF_2018_024</td>
</tr>
</tbody>
</table>

Brand New!

Single production has model dependence:

- Results today shown with a generalized coupling strength, $\kappa=0.5$.
**Single B → Hb**

**Goal:** $B \rightarrow Hb$ in the diphoton decay mode

**Selection:** 2 photons, $\geq 1$ forward jet, $\geq 1$ b-tagged jet, $m_{\gamma\gamma b} > 300$ GeV, and $|y^*| < 1.1$.

**Backgrounds:** Higgs backgrounds from simulation, continuum (e.g. $\gamma\gamma$+jet) background from data-driven estimate.

![Diagram of B → Hb process](image)

**Signal**
- Higgs background
- Continuum background

**Final discriminant**
- Fixed to MC prediction
- Floating normalization

<table>
<thead>
<tr>
<th>$m_{\gamma\gamma b}$ [GeV]</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>$m_B$</td>
<td>Events</td>
</tr>
</tbody>
</table>

**Data sidebands**

![Plot of m_{\gamma\gamma b} vs. Events](image)
Single $B \rightarrow Hb$ (2)

With $\kappa=0.5$, a single vector-like $B$ is excluded below 1210 GeV.
Single T → Zt

**Goal:** Target ≥2 e/μ decay modes consistent with Z boson decay.

**Two signal regions** with ≥ 1 b-tagged and ≥ 1 forward jets:

- **Dilepton:** $p_T^{ll} > 200$ GeV, ≥ 1 top-tagged large-radius jet, $(H_T + E_T^{miss}) < m_{Zt}$
- **Trilepton:** $p_T^{ll} > 150$ GeV, $p_T^{l,\text{lead}} > 200$ GeV, $H_T \times n_{\text{jets}} < 6$ TeV

**Backgrounds:** Constrained in the fit by dedicated control regions.

![Diagram of signal and background processes](diagram.png)
Conclusions

ATLAS has a broad VLQ program, and has had many public results within the last year.

Today I have focused on the most recent of these results in pair and single production of VLQs.

No evidence of VLQs has yet emerged, but the full run-2 dataset could be hiding new discoveries!
Backup
VLQ Combination

Combination includes all the featured analyses, and also...

BDTSR

$\text{BB} \rightarrow W(\rightarrow l\nu)t + X$

$\text{ATLAS}$

$\sqrt{s} = 13 \text{ TeV}$

$36.1 \text{ fb}^{-1}$

$\text{BDT discriminant}$

Data / Pred.

$\text{Events / bin}$

$\text{ATLAS}$

$\sqrt{s} = 13 \text{ TeV}$

$36.1 \text{ fb}^{-1}$

$\text{Signal Region}$

Post-Fit

Data / Pred.

$\text{Events / bin}$

$\text{BDTSR}$

$\text{Signal Region}$

Post-Fit

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$\text{Events / bin}$

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$\text{Signal Region}$

Post-Fit

Data / Pred.

$\text{Events / bin}$
VLQ Combination

Combination includes all the featured analyses, and also...

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

**Signal region**

$\text{ATLAS}$

$\mathbf{TT} \rightarrow Z(\rightarrow \nu \nu)t + X$

$m_{t^\prime} = 1.1$ TeV

$B(Zt,Ht,Wb) = (0.8, 0.1, 0.1)$

**Events / 100 GeV**

**$E_T^{\text{miss}}$ [GeV]**

**Search regions**

**Post-fit (Bkg-only)**

**TT$\rightarrow H(\rightarrow bb)t + X$**

**Data / Bkg**

**Events**

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

**1-lepton**

**0-lepton**

**Data**

**$t\bar{t}$ + light-jets

**$t\bar{t}$ + $\geq 1b$**

**Non-$t\bar{t}$

**Total Bkg unc.**
VLQ Combination

Combination includes all the featured analyses, and also...

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

**B\bar{B} \rightarrow Wt+X 1-lepton**
- SU(2) singlet
- SU(2) (T B) doublet
- SU(2) (B Y) doublet

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

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

**T\bar{T} \rightarrow Wb+X 1-lepton**
- SU(2) singlet
- SU(2) doublet
VLQ Combination

Combination includes all the featured analyses, and also…
The ATLAS $B \rightarrow H(\rightarrow \gamma \gamma)b$ is comparable to CMS $B \rightarrow H(\rightarrow bb)b$ at high mass and stronger at low mass.
The results of the search interpreted in terms of:

- Couplings to SM particles (W, Z)
- The mixing angle between T quark and top quark.
Pair-Production $T(B) \to Zt(Zb)$ Results

The results in terms of a grid of branching ratios for both T and B VLQs.

Exclusions of $m_{VLQ} > 1.2 \ (1.3)$ TeV in the Z-corner for B (T).
Fully-Hadronic VLQ: DNN-tagging

**ATLAS Simulation Preliminary**

- $\sqrt{s} = 13$ TeV
- vRC jets
- $|\eta| < 2.5$
- 150 < $p_T$ < 2000 GeV
- m > 40 GeV

- $V$-boson jet
- Higgs-boson jet
- Top-quark jet
- Background jet

**Background rejection**

- vRC jet $p_T$ [GeV]

- Signal efficiency
- Background rejection

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- vRC jet $p_T$ [GeV]

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Fully-Hadronic VLQ: Signal Regions
Fully-Hadronic VLQ: Results

Results for the Fully-Hadronic VLQ Search

**ATLAS** Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \) VLQ All-Hadronic

- Observed limit

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

- Observed limit
Same Sign Dilepton/Trilepton

Pair-produced VLQ Results for the Same Sign Dilepton/Trilepton Search