Search for Vector-Like Quarks

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Why Vector-Like Quarks?

• VLQ are colored, fractionally-charged fermions that are non-chiral under SU(2)
  - why search for these particular particles?

• Well-motivated:
  - appear in many BSM models (Little Higgs, extra dimensions, etc)
  - cancel quadratic divergences in Higgs mass
  - (maybe) explain fermion mass hierarchy

• Allowed
  - not constrained by Higgs or FCNC measurements

• Accessible at the LHC
  - mass $< \sim 2$TeV to preserve naturalness
VLQ Phenomenology

- Both “normal” ($-1/3$, $2/3$) and “exotic” ($-4/3$, $5/3$) charges possible
- Can appear as SU(2) singlets, doublets, or triplets
- Natural models tend to favor coupling to 3rd-gen SM quarks
- Production via QCD (pair) or EW (single) interactions

Cross section depends only on mass

Cross section depends on mass and EW coupling
Both charged- and neutral-current decays are possible for $B$ and $T$:

- $B \rightarrow Zb, Hb, Wt$
- $T \rightarrow Zt, Ht, Wb$

BRs are constrained in some models

Wide variety of potential signatures

But the general case should be considered as well

JHEP 0911, 030 (2009)
General Strategy

• Searches are typically targeted toward a particular VLQ in a particular decay mode
  - often substantial cross-sensitivity exists

• Backgrounds estimated using:
  - MC for irreducible sources (e.g. Pythia, Sherpa, POWHEG…)
  - data-driven methods for reducible sources (i.e. fake/non-prompt leptons and electron charge misID)

• Data assessed for evidence of VLQ by either counting number of events passing selection or from the distribution of a sensitive variable

• Limits are set at 95% CL using the CLS method
Search for $T \to Zt+X$

- Assume $Z$ decays to $\nu\nu$, with a charged lepton from one of the other objects.
- Signature: 1 lepton, $\geq 4$ jets ($\geq 1$ $b$-tagged, $\geq 2$ large-radius), $E_T^{\text{miss}}$
- Control regions used to assess background modeling.

Signal region is blinded until control regions are understood.
Search for $T \to Zt+X$

- Then compare yields to SM expectation in:
  - ‘validation regions’ with small signal contribution
  - signal region

- One key variable: $m_{T2}$
  - this is a ‘partial mass’ of particles with invisible decay products
  - kinematic endpoint is at parent particle mass
  - used to suppress $W$ and top backgrounds
Search for $T \rightarrow Zt + X$

- Good agreement between observed yield and SM expectation in signal region
- Proceed to setting limits in various scenarios:

Singlet model BRs

For any BRs

- Observed limit
- Expected limit
- $\pm 1 \sigma$
- $\pm 2 \sigma$
- $T\bar{T}$ production
- SU(2) singlet

870 GeV

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Limit at 95% CL

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Observed 95% CL mass limit [GeV]

BR($T \rightarrow Ht$)

BR($T \rightarrow Wb$)
Search for $T \rightarrow Wb + X$

- Final-state objects are similar to $T \rightarrow Wb$ search
  - one lepton, $\geq 4$ jets ($\geq 1 b$-tagged), $E_{T\text{miss}}$

- Optimized for $Wb$ by:
  - reconstructing $\nu$ momentum, and requiring $\Delta R(l, \nu) < 0.8$

- defining separate (‘boosted’) SR for events with jet consistent with $W \rightarrow qq$

$S_T \equiv \sum |p_T|$ for jets, $l$, $E_{T\text{miss}}$
Search for $T \rightarrow Wb + X$

- Leptonically-decaying $T$ candidate mass used to test for signal

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Search for $T \rightarrow Ht + X$

- Two separate topologies considered: 0-lepton and 1-lepton
  - $E_{T\text{miss}} > 200$ GeV for 0-lepton events
  - $Ht$ signature selected by requiring $\geq 2$ $b$-tagged jets

- Several signal regions defined, based on:
  - number of $b$-tagged jets
  - number of $R = 1.0$ jets consistent with Higgs or top decay
  - kinematic variables
    - these allow separate sensitivity to low- and high-mass signals
Search for $T \rightarrow Ht + X$

- Variable used to test for signal is $m_{\text{eff}}$:
  
  $$m_{\text{eff}} \equiv \sum |p_T|_{\text{jets,l}, E_T^{\text{miss}}}$$

- Distribution in the most sensitive signal regions:
Search for $T \rightarrow Ht + X$

- Limits with all signal regions combined
  - both 0- and 1-lepton

**ATLAS** Preliminary

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

Ht+X Combination

$1020$ GeV

95% CL mass limit [GeV]
Search using same-sign leptons

- Events with 2 like-charge leptons are rare in SM
  - low background $\rightarrow$ sensitive to many BSM effects, incl. VLQ
- Challenge: understanding of rare backgrounds: $e$ charge mis-ID, fake/non-prompt leptons
- Multiple SRs defined
  - allows sensitivity to $B$, $T$, and $T^{5/3}$ VLQ

<table>
<thead>
<tr>
<th>Definition</th>
<th>Name</th>
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<tbody>
<tr>
<td>$e^+e^-+\mu^+\mu^-+\mu^+{\bar{\mu}}^{-}$, $N_{\text{jets}} \geq 2$</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
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<tr>
<td>$N_b = 1$</td>
<td>SR0</td>
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<tr>
<td>$N_b = 2$</td>
<td>SR1</td>
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<tr>
<td>$N_b \geq 3$</td>
<td>SR2</td>
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<tr>
<td>$H_T \geq 700$ GeV</td>
<td>$40 &lt; E_T^{\text{miss}} &lt; 100$ GeV</td>
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<td>$N_b = 1$</td>
<td>SR3</td>
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<tr>
<td>$E_T^{\text{miss}} \geq 100$ GeV</td>
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<td>$N_b = 2$</td>
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<td>$40 &lt; E_T^{\text{miss}} &lt; 100$ GeV</td>
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<td>$E_T^{\text{miss}} \geq 100$ GeV</td>
<td>SR7</td>
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<tr>
<td>$N_b = 3$</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
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<tr>
<td>$N_b \geq 3$</td>
<td>SR8</td>
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Search using same-sign leptons

- No excess seen. Resulting limits:

\[ \text{ATLAS Preliminary} \]
\[ \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]

\begin{align*}
\text{SS dilepton / trilepton + b-jets} \\
\text{Observed limit} \\
\text{Expected limit} \\
\text{\pm 1\sigma} \\
\text{\pm 2\sigma} \\
\text{Theory (NNLO)}
\end{align*}

\[ \begin{array}{c|c}
\text{780 GeV} & \text{830 GeV} \\
\end{array} \]
Search for single VLQ production

- Cross section depends on $WQb$ coupling
- Can become dominant mechanism at high VLQ mass:

• Search focussed on $T/Y \rightarrow Wb+X$

• Selection:
  - 1 lepton, 1 high-$p_T$ b-tagged jet, $E_{T\text{miss}}$
  - no additional high-$p_T$ central jets
  - $\geq 1$ forward jet

JHEP 0911, 030 (2009)
Search for single VLQ production

- Reconstructed VLQ mass used to test for signal

ATLAS-CONF-2016-072

ATLAS Preliminary

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

\( Q \rightarrow Wb, Q = T \text{ or } Y \)

Post-Fit

ATLAS Preliminary

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

\( Q \rightarrow Wb, Q = T \text{ or } Y \)

SR

95% CL Exclusion Limits on Coupling

\( \frac{W_b}{C_\nu} \)

Observed

Expected \( \pm 1 \sigma \)

Expected \( \pm 2 \sigma \)
Summary

• ATLAS is pursuing a broad search for vector-like quarks
  - using multiple decay channels to cover all possible branching ratios
• No evidence for their existence uncovered so far
• Still to come:
  - updates using the full 2016 data sample
    ✦ including channels not presented here
  - combination of searches to obtain maximal sensitivity
  - an additional ~70 fb\(^{-1}\) of data to be collected by end of 2018