Searches for vector-like quarks and $t\bar{t}$ resonances with the ATLAS detector

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Standard Model can’t be considered a complete description of Nature
- Even with the last discovery, the famous Higgs boson

Physics Beyond the SM
- Matter-antimatter asymmetry
- Naturalness problem of the SM

In this talk
- Vector-like quarks (VLQs)
- New particles decaying to $t\bar{t}$

All analyses using 14.3 fb$^{-1}$ of ATLAS data @ 8 TeV
Motivation

- Searches that aimed to solve some of the **limitations of the SM**
- Models that could explain **matter-antimatter asymmetry** 
  \[ \mu \mu \text{ channel, } m(Z_b) = 545 \text{ GeV} \]
  \[ m_{tt\text{reco}} = 2.6 \text{ TeV} \ t \bar{t} \text{ candidate} \]

- VLQs appear in many **BSM models**: GUTs, little Higgs, composite Higgs, ...
  - **Left** and **right-handed** components transform in the same way under the EW group
  - Couple preferentially with 3\textsuperscript{rd} generation quarks
- **At LHC**, exotic heavy quarks would be produced **predominantly** in pairs via the strong interaction for masses below **1 TeV**
Pair production of new heavy quarks (T/B) → Z(t/b)

ATLAS-CONF-2013-056

- Heavy quark pair production and vector-like decay modes
  - $+\frac{2}{3}$ T or $-\frac{1}{3}$ B VLQs
  - $T \to Zt$ or $B \to Zb$
  - $T\bar{T}$ and $B\bar{B}$ simulation with PROTOS

**Selection:**
- Two oppositely charged leptons
- Two or more b-jets
- $p_T(Z) > 150$ GeV
- $H_T(jets) > 600$ GeV
- $m(Z,b)$ discriminating variables used for the hypothesis test
Pair production of new heavy quarks \((T/B) \rightarrow Z(t/b)\)

- Absence of signal-like events in the \(m(Z,b)\) distribution
- Set upper limits 95\% C.L. on pair production cross section of VLQs for [350, 850] GeV masses

**Mass Limits:**

<table>
<thead>
<tr>
<th>VLQ</th>
<th>Observed [GeV]</th>
<th>Expected [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet B quark</td>
<td>645</td>
<td>635</td>
</tr>
<tr>
<td>Doublet B quark</td>
<td>725</td>
<td>720</td>
</tr>
<tr>
<td>Singlet T quark</td>
<td>585</td>
<td>550</td>
</tr>
<tr>
<td>Doublet T quark</td>
<td>680</td>
<td>660</td>
</tr>
</tbody>
</table>

- Exclusion limits for \(B\bar{B} \ (T\bar{T})\) hypothesis in the \((Wt, Hb)\) branching ratio plane for \(B \ (T)\) masses in back-up slides

ATLAS-CONF-2013-056
Search for heavy top-like quark pair production ($T\bar{T}$) into $Wb$

**Pre-Selection:**
- One lepton (electron or muon)
- $4 \leq N_{jets} < 6$, $1 \leq N_{b-jets} < 3$
- $E_T^{miss} > 20$ GeV
- $E_T^{miss} + m_T(W) > 60$ GeV

<table>
<thead>
<tr>
<th>Loose selection</th>
<th>Preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1 \ W_{had}$ candidates</td>
<td></td>
</tr>
<tr>
<td>$H_T &gt; 800$ GeV</td>
<td></td>
</tr>
<tr>
<td>$p_T(b_1) &gt; 160$ GeV, $p_T(b_2) &gt; 80$ GeV</td>
<td></td>
</tr>
<tr>
<td>$\Delta R(\ell, \nu) &lt; 1.2$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tight selection</th>
<th>Loose selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\min \Delta R(\ell, b) &gt; 1.4$, $\min \Delta R(W_{had}, b) &gt; 1.4$</td>
<td></td>
</tr>
</tbody>
</table>

Apply techniques to identify $W_{had}$
- **Single jet** with $p_T > 250$ GeV
- **Dijet system** with $p_T > 200$ GeV, $\Delta R(j, j) < 0.8$
Pair production of new heavy quarks (T) → Wb

- **Interpreted as:**
  - Chiral 4th generation T quark
  - Vector-like quark

4th generation: \( m_T > 740 \) (700) GeV, most stringent limit to date

VLQ: \( m_T > 505 \) (630) GeV

Heavy top-like quarks $\rightarrow$ Ht (lepton+jets)

- $T\bar{T}$ production search, $T \rightarrow H(\rightarrow b\bar{b})t$
- Possible final states: $Ht\bar{H}t$, $HtZ\bar{t}$, $HtWb$
- Selection:
  - One high $p_T$ lepton
  - $\geq 6$ jets, $\geq 2$ b-tags
  - $E_T^{\text{miss}} > 20$ GeV
  - $E_T^{\text{miss}} + m_T(W) > 60$ GeV
- Three channels:
  - 2 ($H_T < 700$ GeV), 3 and $\geq 4$ b-tags
  - $t\bar{t}$ dominant background
- $H_T$ excellent discriminating variable

Heavy top-like quarks → Ht (lepton+jets)

- $H_T$ spectra checked in the 3 channels
- No data excess found
- Upper limits on the $T\bar{T}$ production cross section times BR
  - Main systematics: b-tagging, jet energy scale and modelling

**ATLAS-CONF-2013-018**
Same-sign dileptons and b-jets

- **Promising:** small SM contribution
- **Exotic Models:**
  - Pair production of chiral $b'$ quarks
  - Pair production of VLQ
  - 4 top quark production
  - Same-sign top quark production
- **Pre-selection:**
  - 2 leptons same-sign
  - 2 or 3 jets, $\geq 1$ b-tagged jet
  - $E_T^{miss} > 40$ GeV
  - $m_{ll} > 15$ GeV & $\left| m_{ll} - m_Z \right| > 10$ GeV
  - $H_T > 550$ GeV
- **Final Selections:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>$b'$ and VLQ</th>
<th>$tt$</th>
<th>$tttt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T$</td>
<td>$&gt; 650$ GeV</td>
<td>$&gt; 550$ GeV</td>
<td>$&gt; 650$ GeV</td>
</tr>
<tr>
<td>$N_{b-jets}$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>Charge</td>
<td>$\pm\pm$</td>
<td>$++$</td>
<td>$\pm\pm$</td>
</tr>
</tbody>
</table>

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BSM Searches

June 5, 2014 10 / 16

Same-sign dileptons and b-jets

- Interpretation of several new physics models

<table>
<thead>
<tr>
<th>Variable</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{b'}$</td>
<td>&gt; 0.72 TeV</td>
</tr>
<tr>
<td>$m_B$</td>
<td>&gt; 0.59 TeV</td>
</tr>
<tr>
<td>$m_T$</td>
<td>&gt; 0.54 TeV</td>
</tr>
<tr>
<td>$m_{sgluon}$</td>
<td>&gt; 0.80 TeV</td>
</tr>
<tr>
<td>$m_{KK}$</td>
<td>&gt; 0.90 TeV</td>
</tr>
<tr>
<td>$\sigma_{SS-top}$</td>
<td>&lt; 0.21 pb</td>
</tr>
<tr>
<td>$\sigma_{4-top}$</td>
<td>&lt; 85 fb</td>
</tr>
</tbody>
</table>

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A search for $t\bar{t}$ resonances in lepton+jets events

- Search for new particles decaying into $t\bar{t}$
  - Lepton (electron or muon)+jets channel

- **2 benchmark models:**
  - KKg (MADGRAPH+PYTHIA)
  - Leptophobic topcolor $Z'$ (PYTHIA)

- **Two selections:**
  - **Resolved** (leading jet $\Delta R(l, j) < 1.5$, at least 1 b-tagged jet)
  - **Boosted** ($m_{jet} > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV, $\Delta R(j, j_{small}) > 1.5$, $\Delta \phi(l, j) > 2.3$) ⇒ Elin’s talk

- The $t\bar{t}$ inv. mass is tested for any local excess or deficit of events

A search for $t\bar{t}$ resonances in lepton+jets events

- No significant deviation from the expected background is found
- Upper limits on the $\sigma_{Z'} \times BR(Z' \rightarrow t\bar{t})$ and $\sigma_{KKg} \times BR(KKg \rightarrow t\bar{t})$

Exclusion limits at 95 % CL:
- **Obs:** $0.5 \text{ TeV} < m_{Z'} < 1.8 \text{ TeV}$, **Exp:** $0.5 \text{ TeV} < m_{Z'} < 1.9 \text{ TeV}$
- **Obs:** $0.5 \text{ TeV} < m_{KKg} < 2.0 \text{ TeV}$, **Exp:** $0.5 \text{ TeV} < m_{KKg} < 2.1 \text{ TeV}$
Summary

- No evidence of new physics has been observed
- Set up limits:

<table>
<thead>
<tr>
<th>Particle/process</th>
<th>Limits</th>
<th>Decay mode/Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>B singlet (doublet)</td>
<td>( m_B &gt; 0.65 ) (0.73) TeV</td>
<td>B ( \rightarrow ) Zb</td>
</tr>
<tr>
<td>T singlet (doublet)</td>
<td>( m_T &gt; 0.59 ) (0.68) TeV</td>
<td>T ( \rightarrow ) Zt</td>
</tr>
<tr>
<td>4G T</td>
<td>( m_T &gt; 0.74 ) TeV</td>
<td>T ( \rightarrow ) Wb</td>
</tr>
<tr>
<td>T</td>
<td>( m_T &gt; 0.51 ) TeV</td>
<td>T ( \rightarrow ) Wb</td>
</tr>
<tr>
<td>T singlet (doublet)</td>
<td>( m_T &gt; 0.64 ) (0.79) TeV</td>
<td>T ( \rightarrow ) Ht</td>
</tr>
<tr>
<td>4G ( b' )</td>
<td>( m_{b'} &gt; 0.72 ) TeV</td>
<td>same-sign dileptons</td>
</tr>
<tr>
<td>Same-sign tops</td>
<td>( \sigma_{SS-top} &lt; 0.21 ) pb</td>
<td>same-sign dileptons</td>
</tr>
<tr>
<td>4 tops</td>
<td>( \sigma_{4-tops} &lt; 85 ) fb</td>
<td>same-sign dileptons</td>
</tr>
<tr>
<td>sgluon</td>
<td>( m_{sgluon} &gt; 0.80 ) TeV</td>
<td>same-sign dileptons</td>
</tr>
<tr>
<td>( Z' )</td>
<td>( m_{Z'} &lt; 0.5 ) or ( m_{Z'} &gt; 1.8 ) TeV</td>
<td>( Z' \rightarrow t\bar{t} )</td>
</tr>
<tr>
<td>KKg</td>
<td>( m_{KKg} &lt; 0.5 ) or ( m_{KKg} &gt; 2.0 ) TeV</td>
<td>KKg ( \rightarrow t\bar{t} )</td>
</tr>
</tbody>
</table>

Public Results at:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Thank You!
BACK-UP SLIDES
Pair production of new heavy quarks → Z(t/b)

- Absence of signal-like events in the m(Z,b) distribution
- Set upper limits 95% C.L. on pair production cross section of VLQs for [350, 850] GeV masses
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- Exclusion limits at 95% C.L. for $B\bar{B}$ ($T\bar{T}$) hypothesis in the $(Wt, Hb)$ branching ratio plane for [350, 850] GeV $B$ ($T$) masses