Searches for Vector-like Quarks, $t\bar{t}$ and $tb$ resonances with the ATLAS Detector

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on behalf of the ATLAS Collaboration

ICHEP 2014
July 5th, Beyond the Standard Model
The discovery of the 125 GeV Higgs focuses attention on the hierarchy question.

The top quark is the largest correction to the Higgs mass-squared. Strong motivation for searches for new physics in the top sector.

Discussed here are ATLAS searches for:
- Vector-like quarks (VLQs) that mix preferentially with the 3rd generation,
- New vector bosons (Z’, W’, gkk) that couple to the 3rd generation, predicted in many models of new physics: Topcolor, Little Higgs, Composite Higgs, Randall-Sundrum (with warped extra dimensions),...
Vector-like Quarks

- Higgs observation and precision measurements disfavor adding 4th generation quarks with SM-like chiral couplings.
- Left and right-handed components of VLQs have identical electroweak gauge transformations.
  - Singlets: $T_{L,R}, B_{L,R}$
  - Doublets: $\left( \begin{array}{c} X \\ T \end{array} \right)_{L,R}, \left( \begin{array}{c} T \\ B \end{array} \right)_{L,R}, \left( \begin{array}{c} B \\ Y \end{array} \right)_{L,R}$
- Top partner may have a role in regulating the Higgs mass divergence.
- Pair production (strong interaction), dominates at low mass ($< 1$ TeV), only input is $m_Q$.
- Single production (electroweak interaction) becomes larger at higher masses, $m_Q$ and coupling (model dependent) as inputs.
- Diverse final states for analysis. (Assume mixing is entirely 3rd generation).
Searches for Vector-like Quarks

- Search in multi-lepton final states.
- Pair production:
  - \( pp \rightarrow T\bar{T} \rightarrow Zt\bar{t} \) and \( pp \rightarrow B\bar{B} \rightarrow Zb\bar{b} \).
- Single production:
  - \( pp \rightarrow (T \rightarrow Zt)bq \) and \( pp \rightarrow (B \rightarrow Zb)bq \).

Common selection:
- Leptonically (e/\(\mu\)) decaying Z boson
- \( \geq 2 \) central (\(|\eta| < 2.5\)) jets
- \( p_T(Z) > 150 \) GeV.

ATLAS-CONF-2014-036
**Searches for Vector-like Quarks**

- Final discriminant in dilepton channel is $m(Zb)$.  ...in trilepton channel is $H_T(\text{leptons+jets})$.
  - Exactly 2 leptons, $\geq 2$ $b$-tagged jets
    - Single production - $\geq 1$ fwd. jet.
    - Pair production - $H_T(\text{jets}) \geq 600$ GeV.
  - $\geq 3$ leptons, $\geq 1$ $b$-tagged jets
    - Single production - $\geq 1$ forward jet($2.5<|\eta|<4.5$).

![Dilepton Channel](image1)

![Trilepton Channel](image2)

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**ATLAS**

- Preliminary
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV
- Dilepton Channel
- Data
  - $Z$+light
  - $Z$+bottom
  - $t\bar{t}$
  - Other bkg
  - $B\bar{B}$ (650 GeV)
  - $T\bar{T}$ (650 GeV)
  - Uncertainty
  - $\geq 2$ b-tags

- Trilepton Channel
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV
- Data
  - Other bkg.
  - $WZ$
  - $t\bar{t}+V$
  - $B\bar{B}$ (650 GeV)
  - $T\bar{T}$ (650 GeV)
  - $T\bar{B}q$ (650 GeV)
  - Uncertainty
  - $\geq 1$ b-tag
  - $\geq 1$ fwd jet

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**ATLAS-CONF-2014-036**

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Searches for Vector-like Quarks

- Limits are set for pair production in benchmark singlet and doublet models:
  - $B\bar{B}$ singlet/doublet mass 95% CL mass limit 685/755 (679/755) GeV obs. (exp.)
  - $T\bar{T}$ singlet/doublet mass 95% CL limit 735/700 (720/700) GeV obs. (exp.)

- NEW

- 95% CL limits on pair production for all possible branching ratios for the three decay modes (Z,W,H), requiring sum of ratios to be 1.

ATLAS-CONF-2014-036
Searches for Vector-like Quarks

- Combine with previous ATLAS searches in single lepton channel and same-sign dilepton channel.

- 95% CL limits on pair production for all possible branching ratios for the three decay modes (Z,W,H), requiring sum of ratios to be 1.
Searches for Vector-like Quarks

- Set first LHC upper limits (95% CL) on cross section times branching ratio for single production as a function of heavy quark mass ($T$ and $B$).
Searches for $t\bar{t}$ Resonances

- Search for heavy particles decaying into top quark pairs.
- Single lepton signature using exclusive resolved and boosted categories for low and high mass signal regions.
  - Leptonic top reconstructed from lepton ($\mu$ or $e$), jet and missing $E_T$.
  - **Boosted selection**: hadronic top reconstructed as one anti-$k_T$, radius 1.0 jet.
    - Apply jet trimming, jet $p_T$, $\eta$, mass, and substructure selection to reduce background.
    - Large separation between hadronic and leptonic components.
  - **Resolved selection**: only events that fail boosted selection. Hadronic top reconstructed as 2 or 3 anti-$k_T$, radius 0.4 jets.
    - Minimize $\chi^2$ to choose best combination of jets.

➡ See poster by Victoria Sánchez Martínez!

ATLAS-CONF-2013-052
Searches for $t\bar{t}$ Resonances

- Set 95% CL limits on masses for two models of resonances decaying into $t\bar{t}$.
  - Narrow width ($\Gamma/m = 1.2\%$): Topcolor model, leptophobic $Z'$.
    - 1.8 (1.9) TeV, obs. (exp.)
  - Wide width ($\Gamma/m = 15.3\%$): Randall-Sundrum model, Kaluza-Klein gluon.
    - 2.0 (2.1) TeV, obs. (exp.)
Searches for $tb$ Resonances

- Search for new, charged vector boson $W'$ decaying into top quark and bottom quark.
- Both leptonic and hadronic top decays considered.
  - **Leptonic:**
    - Top quark reconstructed from lepton ($\mu$ or $e$), jet and missing $E_T$.
    - 2-3 jets, $\geq 1$ $b$-tagged.
    - Boosted decision tree trained using kinematic variables.
  - **Hadronic - Boosted:**
    - Top quark reconstructed as one anti-$k_T$, radius 1.0 jet.
    - Apply jet trimming, jet $p_T$, $\eta$, and substructure selection to tag top quark.
    - 1 or 2 $b$-tagged jets, one opposite to top tagged jet ($\Delta R > 2.0$).
Searches for $tb$ Resonances

- 95% CL limits on $m(W')$ for SM-like coupling to fermions ($g_{SM}$).
- For right-handed couplings and $m(\nu_R) > m(W'_R)$ (i.e., no decay to SM leptons: $1.8 \ (1.7)$ TeV, obs. (exp.))
- For a left-handed couplings, w/o interference (or right-handed with $m(\nu_R) << m(W'_R)$): $1.7 \ (1.6)$ TeV, obs. (exp.)
- Reinterpret as limits on non-SM couplings, $g'$ (the $W'$ boson gauge coupling to fermions) in $g'/g_{SM}$ - $m(W')$ plane for left and right handed $W'$.

NEW
Summary

- Searches for new physics that couplings preferentially to the third generation are motivated by a variety of models.

- Presented here is only a selection of recent ATLAS analyses of 8 TeV LHC data searching for vector-like quarks, $t\bar{t}$ and $tb$ resonances.
  - Results are consistent with the SM.
  - Exclude (95% CL) vector-like top and bottom quarks mass < 700 GeV.
  - Exclude (95% CL) $t\bar{t}$ resonances mass < 1.8 TeV (narrow $Z'$) or < 2.0 TeV (wide KK gluon).
  - Exclude (95% CL) $tb$ resonances resonances < 1.7 TeV.

- Analyses have developed new techniques with boosted top quarks and jet substructure. This will be even more important as we search for high mass resonances in the coming higher energy LHC run.

Thank you!
Additional Material
Searches for Vector-like Quarks

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Singlet mass limit [GeV]</th>
<th>Doublet mass limit [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dilepton</td>
<td>Trilepton</td>
</tr>
<tr>
<td>$B\bar{B}$</td>
<td>690 (665)</td>
<td>610 (610)</td>
</tr>
<tr>
<td>$T\bar{T}$</td>
<td>620 (585)</td>
<td>620 (620)</td>
</tr>
</tbody>
</table>

- Expected limits as a function of BR for pair production:

**Expected limits as a function of BR for pair production:**

\[
\mathcal{L} = 20.3 \text{ fb}^{-1}
\]

\[
\text{Zb/t + X}
\]

**Viable coupling parameters are excluded for $T$ masses beyond those excluded by the pair production analysis.**

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ATLAS-CONF-2014-055
Searches for Vector-like Quarks

- Same-sign dilepton search testing both $TT$ and $BB$ production.
  - Ex: Exclude (95% CL) mass of chiral $B < 720$ (760) GeV exp. (obs.)
Searches for Vector-like Quarks

- Single lepton searches for $pp \to T\bar{T} \to WbWb$ or $HtHt$.
  - Ex: $T$ mass limit of < 670 (675) GeV exp. (obs.)

![Graph showing ATLAS Preliminary results for $\sigma(pp \to T\bar{T})$ vs. $m_T$]

$\int L dt = 14.3$ fb$^{-1}$

SU(2) singlet

ATLAS-CONG-2013-060 and ATLAS-CONG-2013-018
Searches for Vector-like Quarks

- Final discriminant in dilepton channel is \( m(Zb) \). Require:
  - Exactly 2 leptons, \( \geq 2 \) \( b \)-tagged jets
    - Pair production - \( H_T(jets) \geq 600 \text{ GeV} \)
    - Single production - \( \geq 1 \) fwd. jet.

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ATLAS-CONF-2014-055

Tim Andeen
Searches for Vector-like Quarks

- Final discriminant in trilepton channel is $H_T(\text{leptons}+\text{jets})$. Require:
  - $\geq 3$ leptons, $\geq 1$ $b$-tagged jets
  - Pair production.
  - Single production - $\geq 1$ fwd. jet.

ATLAS-CONF-2014-055 $H_T(\text{jets}+\text{leptons}) \text{ [GeV]}$

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ATLAS Vector-like Top Summary

$m_T = 350$ GeV  

$m_T = 400$ GeV  

$m_T = 450$ GeV  

$m_T = 500$ GeV  

$m_T = 550$ GeV  

$m_T = 600$ GeV  

$m_T = 650$ GeV  

$m_T = 700$ GeV  

$m_T = 750$ GeV  

$m_T = 800$ GeV  

$m_T = 850$ GeV  

$\mathcal{B}(T \rightarrow H_t)$

$\mathcal{B}(T \rightarrow Wb)$
ATLAS Vector-like Top Summary

$\sqrt{s} = 8$ TeV, $\int L dt = 14.3$ & $20.3$ fb$^{-1}$

$\text{BR}(T \rightarrow H \ell)$

$m_T = 350$ GeV

$m_T = 400$ GeV

$m_T = 450$ GeV

$m_T = 500$ GeV

$m_T = 550$ GeV

$m_T = 600$ GeV

$m_T = 650$ GeV

$m_T = 700$ GeV

$m_T = 750$ GeV

$m_T = 800$ GeV

$m_T = 850$ GeV

SU(2) (T,B) doub.  SU(2) singlet
ATLAS Vector-like Bottom Summary

$\sqrt{s} = 8$ TeV,
$\int L dt = 14.3$ fb$^{-1}$

- 95% CL exp. excl.
- 95% CL obs. excl.

- Same-Sign [ATLAS-CONF-2013-051]
- Zb+X [ATLAS-CONF-2013-086]

$SU(2)$ (B,Y) doub. $SU(2)$ singlet
ATLAS Preliminary
Status: ICHEP 2014
$\sqrt{s} = 8$ TeV, $\int dt = 14.3$ & $20.3$ fb$^{-1}$

- 95% CL exp. excl.
- 95% CL obs. excl.

- Orange: Same-Sign ll [ATLAS-CONF-2013-051]
- Pink: Zb+X [ATLAS-CONF-2014-036]

- SU(2) (B,Y) coub.
- SU(2) singlet

BR(B $\rightarrow$ Hb)

BR(B $\rightarrow$ Wt)
Searches for $t\bar{t}$ Resonances

- $\chi^2$ variable minimized to chose resolved jets:

$$
\chi^2 = \left[ \frac{m_{ij} - m_W}{\sigma_W} \right]^2 + \left[ \frac{m_{ijb} - m_{ij} - m_W}{\sigma_{th-W}} \right]^2 + \left[ \frac{m_{jlv} - m_{vl}}{\sigma_{vl}} \right]^2 + \left[ \frac{(p_{T,ijb} - p_{T,jlv}) - (p_{T,th} - p_{T,tl})}{\sigma_W} \right]^2
$$

- Jet trimming (removal of “soft”, low $p_T$ components of jet) is done to reduce sensitivity to pile-up.
 Searches for $t\bar{t}$ Resonances

- Jet mass and the splitting scale are used to select top candidate jets.
- $\sqrt{d_{12}}$ is the $k_T$ splitting scale between the final 2 sub-jets after re-clustering with $k_T$ jet algorithm.

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**ATLAS-CONF-2013-052**
Searches for $t\bar{t}$ Resonances

- Final selection in $\mu$ resolved category and $e$ boosted category.

ATLAS-CONF-2013-052
Searches for \( tb \) Resonances

- Jet substructure variables:

  \[
  \sqrt{d_{12}} \quad \tau_{32} \quad \tau_{21}
  \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{d_{12}} )</td>
<td>&gt; 40 GeV</td>
</tr>
<tr>
<td>( \tau_{32} )</td>
<td>&lt; 0.65</td>
</tr>
<tr>
<td>( \tau_{21} )</td>
<td>[0.4, 0.9]</td>
</tr>
</tbody>
</table>

  - \( \sqrt{d_{12}} \) is the \( k_T \) splitting scale between the final 2 sub-jets after re-clustering with \( k_T \) jet algorithm.
  - \( \tau_{ij} \) is ratio of \( N \)-subjettiness, the compatibility of a large-R jet with \( N \) subjets. Peaks closer to 0 for \( i \)-subjet like jets.
Searches for \( tb \) Resonances

- Background fit, shown with MC and data driven backgrounds.
Searches for $tb$ Resonances

- 1 and 2 $b$-tag results.
Searches for \( tb \) Resonances

- Reinterpret as limits on non-SM couplings in \( g'/g_{SM} - m(W') \) plane for left handed \( W' \). \( V_{ij} \) is CKM/diagonal matrix for quarks/leptons.

\[
\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left( g'_{R_{ij}} (1 + \gamma^5) + g'_{L_{ij}} (1 - \gamma^5) \right) W'^\mu f_j + h.c.
\]

\[ W'_L \]

-observed
- expected
\( \pm 1 \sigma \)

**ATLAS Preliminary**

\[ \int \mathcal{L} dt = 20.3 \text{ fb}^{-1} \]

\( \sqrt{s} = 8 \text{ TeV} \)
Boosted category improves event selection efficiency in the high mass regions.