Search for pair production of new heavy quarks that decay to a Z boson and a third generation quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Joseph S. Virzi (LBNL)

DPF 2013 Santa Cruz, Ca
Overview

• Introduction and Motivation
• Strategy
• Signal and Control Regions
• Systematic Uncertainties
• Results and Conclusions

• Analysis uses 14.3 fb\(^{-1}\) of 2012 data at 8 TeV
• Use \(M_Q = 600\) GeV as representative example
  – Analysis covers 350 GeV \(\leq M \leq 850\) GeV

See M.S. Cooke’s talk
Analysis Object Definitions

• Light leptons (electrons and muons)
  – $p_T \geq 25$ GeV
  – Isolation: $\Delta R \geq 0.4$ to any jet
  – Electrons have $|\eta| < 2.47$ and exclude crack ($1.37 < |\eta| < 1.52$)
  – Muons have $|\eta| < 2.5$

• Jets
  – Anti-Kt algorithm with Radius Parameter $D=0.4$
  – $p_T \geq 25$ GeV
  – $|\eta| < 2.5$
  – Overlap removal against electrons using $\Delta R = 0.2$

• B-tagging
  – Using a multivariate tagger based on track impact parameter and displaced secondary vertices (MV1)
  – MV1 weight at 70% operating point (MV170)

• $u, d, c, s, b$ denote Standard Model (SM) quarks

• $T, B$ denote new t-like, b-like quarks, respectively
• Standard Model (SM) contains 3 generations of leptons and quarks
• Fermions are chiral
  – Left-handed fermions transform as doublets under EW gauge group \( (u, d)_L \)
  – Right-handed fermions transform as singlets
• Many beyond-SM models include new breed of quarks (fermions) where both left- and right-handed components transform in the same manner
  – Vector-like
Flavor Changing Neutral Currents?

• Strong constraints on FCNC for chiral fermions
  – 2 and 3 generations → GIM-suppression
  – 4\textsuperscript{th} generation somewhat less stringent
• Chiral fermion FCNC constraints not applicable to vector-like fermions

OUR SEARCH FOCUSES ON DECAYS VIA THE Z\textsuperscript{0} BOSON
New Heavy Vector-Like Quark (VLQ) Production

FOR MASS $\leq 1$ TeV PREDOMINANTLY PAIR PRODUCED

$Q = T, B$

$q, q' = t, b$

PRODUCTION CROSS SECTION

~75K EVENTS

150 EVENTS
Vector-Like Quarks
What Would They Look Like?

- \((T, B)\) form a weak-isospin doublet?
- \((X, T)\) and/or \((B, Y)\) for weak-isospin doublet?
- \(T\) and/or \(B\) singlets?

SEARCH STRATEGY IS THE SAME FOR ALL SCENARIOS WHERE NEUTRAL CURRENT DECAYS ARE POSSIBLE
Heavy VLQ Decays
Branching Ratios

- Reasonable neutral current branching ratios
  - Better for B than for T
Heavy Vector-Like Quark Signature
“Broad Strokes” Picture - Strategy

• On-shell, high $P_T$ (boosted) leptonic $Z$
  – $76 \text{ GeV} \leq M_Z \leq 106 \text{ GeV}$
  – $pT(Z) \geq 150 \text{ GeV}$
• Select events with $\geq 2$ jets
• Two SM $b$-quarks $\rightarrow b$-jets
• Large additional energy $-$ $H_T = \sum_{\text{jet}} p_T$
• Quark mass gives structure to invariant mass of decay products - $M(Zb)$
$N_{tag}$ as Discriminating Variable

- Events with $Z + \geq 2$ jets
- Signal rich in $b$-jets
- Background relatively poor
$p_T(Z)$ as a Discriminating Variable

- Signal exhibits boosted $p_T(Z)$ profile
- Background much softer

$N_{tag} \geq 2$

$p_T(Z) \geq 150\text{GeV}$
$H_T = \sum_{\text{jets}} p_T^{\text{jet}}$

**Signal exhibits enhanced structure at large $H_T$**

- $N_{\text{tag}} \geq 2$
- $p_T(Z) \geq 150 \text{GeV}$
- $H_T \geq 600 \text{GeV}$

6/11/2013
J.S.Virzi (LBNL)
Invariant Mass of Zb System

- Signal exhibits structure in invariant mass distribution
- Choose highest $p_T$ b-jet as b-candidate
- Works for both T and B
Backgrounds

- Z+jets – dominant
  - Z+light flavor (u,d,s)
  - Z+charm
  - Z+bottom
- top/anti-top quark + jets
- VV+jets (V=W,Z)
- top/anti-top quark + V + jets
- W+jets
Background Details

- **Z+jets modelled with Sherpa and AlpGen**
  - Sherpa used for baseline analysis
  - Extensive comparisons of Sherpa and AlpGen
    - Sherpa uses CT10NLO Parton Distribution Function (PDF)
    - AlpGen uses CTEQ6L1 PDF
- **Top/anti-top matrix element (ME) modelled by POWHEG**
  - Parton Shower (PS) and Hadronization by Pythia
  - CT10NLO PDF
- **Diboson ME modelled by AlpGen**
  - PS and Hadronization by HERWIG
- **Wt and s-channel single top ME production modelled by MC@NLO**
  - PS and Hadronization by HERWIG
- **t-channel single top ME modelled by ACER MC**
  - PS and Hadronization by Pythia
- **All backgrounds normalized to NLO cross sections**
Implement correction process to bring MC closer to data
• MC shapes and rates should agree w/data close to signal region
• Minimize signal contamination in the control region (defined next)
Control Regions/Monte Carlo Corrections

• Reminder: events selected with $Z + \geq 2$ jets
• $Z$+jets sample binned into $N_{\text{tag}} = 0, 1$ or $\geq 2$
• $Z$+jets normalized so that total background prediction for $p_T(Z) \leq 100$ GeV agrees with data in each $N_{\text{tag}}$ bin

• Significant residual slope in $p_T(Z)$ distribution observed (previous slide)
  – Similar slope in each $N_{\text{tag}}$ bin
  – Derive new reweight function $F(p_T)$ in $N_{\text{tag}} = 1$ bin
  – Apply $F(p_T)$ to $N_{\text{tag}} = 2$ bin
• Results of reweights shown next
$N_{\text{tag}} = 0, 1$

$p_T(Z) < 100 \text{ GeV}$

LHS is $H_T$ after $p_T(Z)$ correction

RHS is $M(Zb)$ after $p_T(Z)$ correction
Final Signal Region Distributions

- All corrections applied
Final $M(Zb)$ Distribution

- $\geq 2$ b-tagged jets
- $p_T(Z) \geq 150$ GeV
- $H_T \geq 600$ GeV

- All corrections applied
- Observed distribution consistent with SM prediction
Systematic Uncertainties in the M(Zb) Normalization

<table>
<thead>
<tr>
<th></th>
<th>Z+ jets</th>
<th>$t\bar{t}$</th>
<th>Other bkg.</th>
<th>$B\bar{B}$ (600 GeV)</th>
<th>$T\bar{T}$ (600 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>1.7</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Cross section</td>
<td>7.0</td>
<td>11</td>
<td>28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jet Reco.</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>4.8</td>
<td>5.8</td>
</tr>
<tr>
<td>b-tagging</td>
<td>7.1</td>
<td>13</td>
<td>13</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>e Reco.</td>
<td>1.8</td>
<td>6.8</td>
<td>3.0</td>
<td>3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>$\mu$ Reco.</td>
<td>1.8</td>
<td>2.3</td>
<td>4.9</td>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>Z+ jets rate corr.</td>
<td>9.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Z+ jets $p_T(Z)$ corr.</td>
<td>19</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- Relative uncertainties in %
- Z+jets rate correction uses $p_T(Z) \leq 100$ GeV in $N_{tag} = 1$ bin
  - Uncertainty assessed by comparing use of $50 \leq p_T(Z) \leq 150$ GeV instead
- Z+jets $p_T(Z)$ correction uses reweighting, derived in the $N_{tag} = 1$ bin, applied to $N_{tag} = 2$ bin
  - Uncertainty assessed by comparing use of $N_{tag} = 0$ bin instead
  - Large statistical component
• (T,B) doublet scenario – \( M(T) \leq 680 \) GeV excluded at 95% CL
• T singlet scenario – \( M(T) \leq 585 \) GeV excluded at 95% CL
• (B,Y) doublet scenario $M(B) \leq 725$ GeV excluded at 95% CL
• B singlet scenario $M(B) \leq 645$ GeV excluded at 95% CL
Conclusions

• The search for Vector-Like Quarks did not produce a significant deviation from the predicted SM background in the M(Zb) distribution
• Cross section exclusion plots derived
  – Expected exclusion consistent with observed exclusion
• Branching ratio exclusion plots derived
• Assuming a T(B) singlet model, a new vector-like quark is excluded for with $M_Q \leq 585$ GeV(645 GeV)
• Assuming a (T, B) doublet model, a new vector-like quark is excluded with $M_Q \leq 680$ GeV(725 GeV)
2D Exclusion Limits for Branching Ratios

- Assumes $\text{BR}(T \rightarrow Ht) + \text{BR}(T \rightarrow Wb) + \text{BR}(T \rightarrow Zt) = 1$
2D Exclusion Limits for Branching Ratios

- Assumes $\text{BR}(B \to Hb) + \text{BR}(B \to Wt) + \text{BR}(B \to Zb) = 1$

6/11/2013  J.S. Virzi (LBNL)
Backup Slides
Some Previous Searches for New Heavy Quarks

- \( T \rightarrow W_b \)
  - ATLAS Collaboration
    - ATLAS update [link](https://cds.cern.ch/record/1553199)

- \( T \rightarrow Z_t \)
  - CMS Collaboration

- \( T \rightarrow H_t \)
  - ATLAS-CONF-2013-018

- \( T \rightarrow Z_b \)
  - ATLAS Collaboration

- \( T \rightarrow W_b/tH/tZ \)
  - CMS Collaboration
    - [link](http://cds.cern.ch/record/1557571)
The Analysis

• Select events with Z and ≥2 jets
  – \( Z \rightarrow ee \) (148K events)
  – \( Z \rightarrow \mu\mu \) (203K events)
  – \( 76 \text{ GeV} \leq M(Z \rightarrow \text{light leptons}) \leq 106 \text{ GeV} \)

• Signal Region (SR) – details follow
  – \( N_{\text{tag}} \geq 2 \)
  – \( p_T(Z) > 150 \text{ GeV} \)
  – \( H_T > 600 \text{ GeV} \)

• Discriminating variable is invariant mass of Z + hardest b-jet
  – \( M(Zb) \)

• Control Regions (CR)
  – Compare Monte Carlo (MC) modelling of background against data
  – \( p_T(Z) < 100 \text{ GeV} \)
  – \( N_{\text{tag}} = 0 \) or \( 1 \)

• Normalization of Monte Carlo SM background to DATA

• \( CL_S \) exclusion using \( M(Zb) \) templates

WORKS FOR BOTH NEW TOP-LIKE AND BOTTOM-LIKE QUARKS!
Event Displays

$pp \rightarrow Z\bbbar + \text{jets} \rightarrow e\ebbar + \text{jets}$

$pp \rightarrow Z\bbbar + \text{jets} \rightarrow \mu\mu\bbbar + \text{jets}$
## Event Yields Before/After Corrections

<table>
<thead>
<tr>
<th></th>
<th>$Z^+ \geq 2$jets ($N_{tag} = 1$)</th>
<th>$p_T(Z) &gt; 150$ GeV</th>
<th>$H_T$(jets) &gt; 600 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$+light (before $p_T$ corr.)</td>
<td>$17,000 \pm 1,200$</td>
<td>$1,370 \pm 150$</td>
<td>$78.3 \pm 5.9$</td>
</tr>
<tr>
<td>$Z$+light (after $p_T$ corr.)</td>
<td>$16,700 \pm 1,500$</td>
<td>$1,170 \pm 190$</td>
<td>$68.0 \pm 15.3$</td>
</tr>
<tr>
<td>$Z$+bottom (before $p_T$ corr.)</td>
<td>$15,000 \pm 1,400$</td>
<td>$1,290 \pm 170$</td>
<td>$56.3 \pm 5.0$</td>
</tr>
<tr>
<td>$Z$+bottom (after $p_T$ corr.)</td>
<td>$14,700 \pm 1,400$</td>
<td>$1,110 \pm 180$</td>
<td>$48.8 \pm 11.1$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$2,700 \pm 300$</td>
<td>$61 \pm 9$</td>
<td>$7.8 \pm 2.1$</td>
</tr>
<tr>
<td>Other SM</td>
<td>$900 \pm 300$</td>
<td>$135 \pm 45$</td>
<td>$14.0 \pm 5.2$</td>
</tr>
<tr>
<td>Total SM (before $p_T$ corr.)</td>
<td>$35,600 \pm 2,000$</td>
<td>$2,850 \pm 230$</td>
<td>$156.4 \pm 9.3$</td>
</tr>
<tr>
<td>Total SM (after $p_T$ corr.)</td>
<td>$35,000 \pm 2,000$</td>
<td>$2,470 \pm 265$</td>
<td>$138.5 \pm 19.6$</td>
</tr>
<tr>
<td>Data</td>
<td>$34,955$</td>
<td>$2,480$</td>
<td>$121$</td>
</tr>
<tr>
<td>$B\bar{B}$ ($m_B = 600$ GeV)</td>
<td>$22.5 \pm 3.4$</td>
<td>$18.7 \pm 2.9$</td>
<td>$13.0 \pm 2.4$</td>
</tr>
<tr>
<td>$T\bar{T}$ ($m_T = 600$ GeV)</td>
<td>$15.2 \pm 2.1$</td>
<td>$12.0 \pm 1.6$</td>
<td>$8.0 \pm 1.3$</td>
</tr>
</tbody>
</table>
# Event Yields After Selection

<table>
<thead>
<tr>
<th>Category</th>
<th>$Z+ \geq 2$-jets ($N_{\text{tag}} \geq 2$)</th>
<th>$p_T(Z) &gt; 150$ GeV</th>
<th>$H_T(\text{jets}) &gt; 600$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z+$ light</td>
<td>850 $\pm$ 240</td>
<td>58 $\pm$ 17</td>
<td>4.3 $\pm$ 1.8</td>
</tr>
<tr>
<td>$Z+$ bottom</td>
<td>3380 $\pm$ 470</td>
<td>301 $\pm$ 55</td>
<td>17.8 $\pm$ 4.8</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1730 $\pm$ 320</td>
<td>31 $\pm$ 6</td>
<td>5.1 $\pm$ 1.4</td>
</tr>
<tr>
<td>Other SM</td>
<td>190 $\pm$ 60</td>
<td>29 $\pm$ 10</td>
<td>3.0 $\pm$ 1.2</td>
</tr>
<tr>
<td>Total SM</td>
<td>6,150 $\pm$ 620</td>
<td>419 $\pm$ 59</td>
<td>30.2 $\pm$ 5.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Data</th>
<th>$B\bar{B}$ ($m_B = 600$ GeV)</th>
<th>$T\bar{T}$ ($m_T = 600$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>6,097</td>
<td>31.0 $\pm$ 4.3</td>
<td>21.9 $\pm$ 2.8</td>
</tr>
<tr>
<td>$B\bar{B}$ ($m_B = 600$ GeV)</td>
<td>386</td>
<td>25.7 $\pm$ 3.6</td>
<td>17.1 $\pm$ 2.2</td>
</tr>
<tr>
<td>$T\bar{T}$ ($m_T = 600$ GeV)</td>
<td>26</td>
<td>19.8 $\pm$ 2.7</td>
<td>12.2 $\pm$ 1.7</td>
</tr>
</tbody>
</table>