Searches for resonances decaying to Standard Model third generation quarks and leptons

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On behalf of the ATLAS Collaboration

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Presenting results from ATLAS @ 8 TeV for particle searches:

- $W' \rightarrow t\bar{b}$ (ATLAS-CONF-2013-050)

- $Z'/g_{KK} \rightarrow tt \rightarrow W^+ b W^- \bar{b}$ (ATLAS-CONF-2013-052)

- High-mass $Z'_{SSM} \rightarrow \tau_{had}\tau_{had}$ resonances (ATLAS-CONF-2013-066)
LHC luminosity & the ATLAS detector

All detectors/triggers
good for physics: 95.8 %
**ATLAS exotic searches summary**

*Focusing on recent results with ~14 - 20 fb⁻¹ (2012 data @ 8 TeV):*

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)

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**ATLAS Exotics Searches - 95% CL Lower Limits (Status: May 2013)**

[Diagram showing various exotic search results with mass limits on different particles.]
Searches with 3\textsuperscript{rd} generation quarks & leptons

3\textsuperscript{rd} generation quarks:

- Questions on mass hierarchy within SM
- top & bottom quarks \rightarrow preferred final state in case of mass-dependent couplings

Challenges:

- Experimental identification of $b$-jets, especially at high $p_T$
- Theory and modeling uncertainties in top physics
- Substructure-based top-tagging & lepton isolation for boosted tops

Tau Leptons:

- Backgrounds to leptons reduced w.r.t. hadronic signatures, thus smaller cross-sections can be probed
- Availability of known peaks to test background predictions and detector performance

Challenges:

- Small leptonic branching ratios at high masses
- Soft leptons for some models \rightarrow difficult detection
- Jets faking leptons are not always well modeled
Search for $W' \rightarrow t\bar{b} \rightarrow l\nu b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV
This search uses $\mathcal{L} = 14.3$ fb$^{-1}$ and looks at final states with electrons or muons.

Several BSM models predict $W'$ bosons:

- Kaluza-Klein excitations of the SM $W$ boson, techni-colour models, Little Higgs

- In many BSM theories the $W'$ boson is expected to couple more strongly to the 3$^{rd}$ generation quarks than to the 1$^{st}$ or 2$^{nd}$

- Easier to look for $t\bar{b}$ final states than pure $jj$

- The analysis uses a multivariate method based on boosted decision trees (BDT)

- The search range covers $0.5 < M_{W'} < 3.0$ TeV, with R- or L-handed $W'$-boson chiralities.
**Backgrounds, triggers & Event selection**

- **Main contribution:** $\bar{t}t$ production, $W+$jets, $W+$light jets or $W+c/\bar{c}$ ($b\bar{b}$) processes (possible misidentification of light-quarks as $b$ jets)

- **Smaller contribution:** single top production (t-channel, $Wt$ and s-channel), $WW$, $WZ$, $ZZ$, $Z+$jets events, multijet events

**Triggers:**

- electron object: $E_T > 60$ GeV, or $E_T > 24$ GeV with an isolation requirement

- muon object: $p_T > 36$ GeV, or $p_T > 24$ GeV with an isolation criterion

**Event Selection:**

- Data-quality requirements (proper functioning of the detector and trigger subsystems, as well as LHC stable beam periods)

- Isolated electron candidates with $p_T > 30$ GeV, $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$; muon candidates should have a $p_T > 30$ GeV and $|\eta| < 2.5$
Event selection contd.

- Jets are reconstructed using the anti-\(k_t\) algorithm with \(R = 0.4\), with \(p_T > 25\) GeV and \(|\eta| < 2.5\)

- \(E_T^{\text{miss}} > 35\) GeV (to reduce the multijet BG)

- \(b\)-jets identified using a NN-based \(b\)-tagger (70% eff. and light-jets rejection factor = 135)

- \(PV \geq 1\) with \(N_{\text{trk}} \geq 5\) associated to it and with exactly one lepton (electron or muon), \(p_T^{\text{miss}}\), and 2 or 3 jets with \(\geq 1\) \(b\)-jet

- Events must pass a selection criteria, defined as \(E_T^{\text{miss}} + m_T(W) > 60\) GeV
Analysis strategy

- BDT is used for discrimination of signal to background

- Main discriminants: $m_{tb}$, $p_T$(top) out of 14 variables (2-jet) / 13 variables (3-jet)

- separation between lepton and $b$-jet

- BDT output and $p_T$ spectrum for data, signal and background in a signal region with 2 $b$-jets
Results

- No data excess over the expected SM background is observed in the BDT output → set limits on $W'$ with SM couplings (effective model) @ 95% CL:
  - $m(W'_L) > 1.74$ TeV
  - $m(W'_R) > 1.84$ TeV

<table>
<thead>
<tr>
<th>$W'$ mass (TeV)</th>
<th>$W'_L$ Theory</th>
<th>$W'_L$ Obs. limit</th>
<th>$W'_R$ Theory</th>
<th>$W'_R$ Obs. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>17</td>
<td>4.0</td>
<td>23</td>
<td>2.2</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.24</td>
<td>1.4</td>
<td>0.17</td>
</tr>
<tr>
<td>1.5</td>
<td>0.13</td>
<td>0.075</td>
<td>0.17</td>
<td>0.051</td>
</tr>
<tr>
<td>2.0</td>
<td>0.022</td>
<td>0.064</td>
<td>0.028</td>
<td>0.056</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0044</td>
<td>0.11</td>
<td>0.0054</td>
<td>0.10</td>
</tr>
<tr>
<td>3.0</td>
<td>0.0011</td>
<td>0.20</td>
<td>0.0013</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Search for $t\bar{t}$ resonances decaying to leptons and jets
**Topcolor**: introduces a new leptophobic Z-like boson: $Z'$.

- Narrow resonance: width 1.2% of the mass.
- Strong coupling to first and third generation of quarks.

The model explains the top mass and EWSB.

**Randall-Sundrum**: Kaluza-Klein gluons arise in this model.

- Broad resonance: width 15% of the mass.
- Strongly coupled to the top quark.

This model introduces a single warped extra dimension and explains the hierarchy problem.
Backgrounds & analysis strategy

- **Data**: collected in 2012 @ 8 TeV with \( \mathcal{L} = 14 \text{ fb}^{-1} \).
- **BG**: SM \( \bar{t}t \), \( W/Z + \text{jets} \) (shape), single top and di-boson → estimated from MC
- \( W + \text{jets} \) normalization (charge-asymmetry of W) and multijet (matrix method) → estimated from data
- **Event selection**: \( \bar{t}t \) events are selected in the \( e \) or \( \mu + \text{jets} \) channels using two different topologies: boosted and resolved.

- **Discriminant variable**: \( \bar{t}t \) invariant mass
- **Limits**: computed using a Bayesian technique
Event selection

- **Lepton selection**: one isolated lepton
  - Electron: $E_T > 25$ GeV and $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - Muon: $p_T > 25$ GeV and $|\eta| < 2.5$

- **Multijet background rejected by**:
  - e-channel: $E_T^{\text{miss}} > 30$ GeV and $m_T > 30$ GeV
  - $\mu$-channel: $E_T^{\text{miss}} > 20$ GeV, $E_T^{\text{miss}} + m_T > 60$ GeV

\[
m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \Delta \phi)}
\]
Jet selection

- anti-$k_t$ algorithm used

- small-radius jets ($R = 0.4$): $p_T > 25$ GeV, $|\eta| < 2.5$

- large-radius jets with trimming applied ($R = 1.0$): $p_T > 300$ GeV and $|\eta| < 2.0$

- **Boosted**: $\geq 1$ small-radius jet: highest $p_T$ jet with $R(\ell; j_{0.4}) < 1.5$

  $\geq 1$ large-radius jet: $m_{\text{jet}} > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV, $\Delta R(j_{1.0}, j_{0.4}) > 1.5$ \& $\Delta \Phi(j_{1.0}; \ell) > 2.3$

- or **resolved**: 4 small-radius jets: $p_T > 25$ GeV, $|\eta| < 2.5$

- or **3 small-radius jets**: accepted if $m_{\text{jet}} > 60$ GeV for one of these jets

  Resolved topology is applied only if the boosted selection failed

- $\geq 1$ b-tagged jet

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**Boosted selection**

**Resolved selection**
Data & BG

- $\bar{t}t$ invariant mass computed from the four-momenta of the objects in the event

- **Resolved:** uses neutrino $p_{Z}$ and a $\chi^2$ algorithm to select the best assignment to jets

- **Boosted:** no ambiguity in the assignment of jets

- Hadronic decay $\rightarrow$ large radius jet

- Semi-leptonic decay $\rightarrow$ Neutrino $p_{Z}$, high-$p_T$ lepton and a small radius jet
Resolved + boosted distributions

\[
\int L \, dt = 14.2 \, fb^{-1}
\]

Data/Bkg

\begin{tabular}{|c|c|c|}
\hline
\textbf{\(e + \mu\)} & \textbf{Resolved} & \textbf{Boosted} \\
\hline
Predicted Data & 283 000 ± 39 000 & 5 600 ± 1 200 \\
Data & 280 251 & 5 122 \\
\hline
\end{tabular}

Observed and expected number of background events

Good agreement between data and expected background within uncertainties
Limits on $Z'$ and $g_{KK}$

Exclusion ranges @ 95% C.L:

- Expected exclusion:
  - $0.5 \text{ TeV} < m_{Z'} < 1.8 \text{ TeV}$
  - $0.5 \text{ TeV} < g_{KK} < 2.0 \text{ TeV}$
Search for high-mass $\tau_{\text{had}}\tau_{\text{had}}$ resonances
Sequential Standard Model (SSM) is a benchmark model that contains a heavy neutral gauge boson, $Z^{'}_{SSM}$, with the same couplings to fermions as the $Z$ boson of the SM.

Most stringent limits on $Z^{'}_{SSM}$ in the $e^+e^-$ and $\mu^+\mu^-$ decay channels combined are 2.79 TeV and $\tau_{bad}\tau_{bad}$ 1.4 TeV (5 fb$^{-1}$).

In this analysis using integrated luminosity of 19.5 fb$^{-1}$.

Tau leptons - good probe for new particles whose couplings increase with mass.

Single-tau trigger with $E_T$ threshold of 125 GeV

Primary vertex with at least four associated tracks, each with $p_T > 0.5$ GeV

BG: $Z/\gamma^* \rightarrow \tau\tau$, $W$+jets, $t\bar{t}$, diboson, $Wt$ and s-channel single top events
**Event selection**

- **Hadronic tau** decays are defined as reconstructed jets with either **one** or **three** associated **tracks** reconstructed in the inner detector.

- Hadronic tau decays are identified with a multivariate algorithm that employs BDTs to discriminate against quark and gluon-initiated jets using shower shape and tracking information; the taus must pass a loose BDT tau ID.

- Tau candidates: $p_T \geq 50$ GeV & to be within $|\eta| < 2.47$ (with $1.37 < |\eta| < 1.52$ excluded).

- The analysis vetoes electrons and muons:
  - e-candidates: pass electron veto, $p_T > 15$ GeV and $|\eta| < 2.47$.
  - $\mu$-candidates: $p_T > 10$ GeV and $|\eta| < 2.5$.

- Jets are reconstructed using the anti-$k_t$ algorithm (R=0.4), $p_T > 30$ GeV and $|\eta| < 4.5$.

- Events must contain $\geq 2$ tau candidates and no electrons or muons, with the leading tau $p_T > 150$ GeV.

- Taus are expected back-to-back with $\phi(\tau_1, \tau_2) > 2.7$. 
Results

- No significant excess observed

- A lower limit on the mass of a $Z'_{SSM}$ decaying to $\tau_{had} \tau_{had}$ in the Sequential Standard Model is 1.90 TeV at 95% CL.

The earlier result in the hadronic tau channel for this search placed limits at 1.4 TeV.
No hints of new physics yet for resonances decaying to third generation leptons and quarks

We are pushing the limits into the multi-TeV scale with the current data set

Latest results using the full luminosity from 2012 @ 8 TeV

Run 2 will indeed be a very exciting period, with the increased beam energy and luminosity → expect surprises
Back-up Slides
• Expected BDT output distributions for the background and several $W'_L/W'_R$-boson processes in the 3-jet signal region (ATLAS-CONF-2013-050)
Data and expected BG events in the signal region. Event yields for several mass hypotheses of the R-handed \( W' \) boson shown. The uncertainties account for all systematic effects. (ATLAS-CONF-2013-050)

<table>
<thead>
<tr>
<th>( W'_R ) (mass)</th>
<th>2-jet 2-tag channel</th>
<th>3-jet 2-tag channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 TeV</td>
<td>11800 ± 2700</td>
<td>8200 ± 1800</td>
</tr>
<tr>
<td>1.0 TeV</td>
<td>600 ± 150</td>
<td>660 ± 160</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>42 ± 11</td>
<td>56 ± 13</td>
</tr>
<tr>
<td>2.0 TeV</td>
<td>4.2 ± 1.1</td>
<td>6.2 ± 1.5</td>
</tr>
<tr>
<td>2.5 TeV</td>
<td>0.69 ± 0.17</td>
<td>0.87 ± 0.20</td>
</tr>
<tr>
<td>3.0 TeV</td>
<td>0.22 ± 0.06</td>
<td>0.25 ± 0.06</td>
</tr>
</tbody>
</table>

| \( t\bar{t} \)   | 8300 ± 2100          | 22000 ± 5000         |
| Single-top \( t \)-channel | 1000 ± 270   | 1400 ± 400           |
| Single-top \( Wt \) | 400 ± 80         | 880 ± 170            |
| Single-top \( s \)-channel | 310 ± 90       | 160 ± 50             |
| \( W+jets \)      | 3600 ± 1900        | 4000 ± 5000          |
| Diboson           | 130 ± 60           | 80 ± 40              |
| \( Z+jets \)      | 26 ± 20            | 42 ± 30              |
| Multijets         | 710 ± 350          | 410 ± 210            |

| Total bkg.        | 14400 ± 3100        | 29000 ± 7000         |
| Data              | 14138               | 27759                |
• Observed and expected 95% CL limits on the ratio \( g'/g \), as a function of the mass of the \( W' \) boson, for L- and R-handed \( W' \) bosons (ATLAS-CONF-2013-050)
Data and expected background event yields after the resolved and boosted selections (ATLAS-CONF-2013-052)

### Resolved selection

<table>
<thead>
<tr>
<th>Type</th>
<th>$e+$jets</th>
<th>$\mu+$jets</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>94000 $\pm$ 15000</td>
<td>118000 $\pm$ 19000</td>
<td>211000 $\pm$ 33000</td>
</tr>
<tr>
<td>Single top</td>
<td>6800 $\pm$ 800</td>
<td>8400 $\pm$ 1100</td>
<td>15200 $\pm$ 1900</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>3700 $\pm$ 1800</td>
<td>10000 $\pm$ 5000</td>
<td>14000 $\pm$ 6000</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>16000 $\pm$ 4000</td>
<td>23000 $\pm$ 6000</td>
<td>39000 $\pm$ 10000</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>1800 $\pm$ 400</td>
<td>1800 $\pm$ 400</td>
<td>3600 $\pm$ 800</td>
</tr>
<tr>
<td>Di-bosons</td>
<td>230 $\pm$ 50</td>
<td>320 $\pm$ 60</td>
<td>550 $\pm$ 100</td>
</tr>
<tr>
<td>Total</td>
<td>121000 $\pm$ 17000</td>
<td>162000 $\pm$ 23000</td>
<td>283000 $\pm$ 39000</td>
</tr>
<tr>
<td>Data</td>
<td>119490</td>
<td>160878</td>
<td>280251</td>
</tr>
</tbody>
</table>

### Boosted selection

<table>
<thead>
<tr>
<th>Type</th>
<th>$e+$jets</th>
<th>$\mu+$jets</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>2100 $\pm$ 500</td>
<td>2800 $\pm$ 600</td>
<td>4900 $\pm$ 1100</td>
</tr>
<tr>
<td>Single top</td>
<td>71 $\pm$ 15</td>
<td>105 $\pm$ 22</td>
<td>176 $\pm$ 34</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>39 $\pm$ 19</td>
<td>32 $\pm$ 16</td>
<td>71 $\pm$ 25</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>170 $\pm$ 60</td>
<td>310 $\pm$ 90</td>
<td>480 $\pm$ 140</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>18 $\pm$ 11</td>
<td>33 $\pm$ 8</td>
<td>52 $\pm$ 15</td>
</tr>
<tr>
<td>Di-bosons</td>
<td>2.0 $\pm$ 0.8</td>
<td>1.5 $\pm$ 1.4</td>
<td>3.5 $\pm$ 1.8</td>
</tr>
<tr>
<td>Total</td>
<td>2400 $\pm$ 500</td>
<td>3300 $\pm$ 700</td>
<td>5600 $\pm$ 1200</td>
</tr>
<tr>
<td>Data</td>
<td>2177</td>
<td>2945</td>
<td>5122</td>
</tr>
</tbody>
</table>
Event display for $m_{tt}^{\text{reco}} = 2.6$ TeV e+jets $t\bar{t}$ candidate event
Event display for $m_{tt}^{\text{reco}} = 2.5$ TeV $\mu+$jets $\bar{t}t$ candidate event
Systematic errors for the $T_{\text{had}}T_{\text{had}}$ resonance search (ATLAS-CONF-2013-066)

<table>
<thead>
<tr>
<th>Expected Events</th>
<th>$Z/\gamma^* \rightarrow \tau\tau$</th>
<th>Multijet</th>
<th>$W/Z+$jets</th>
<th>Diboson</th>
<th>SM total</th>
<th>$Z_{\text{SSM}}^{(1750)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.99 ± 0.02</td>
<td>0.17 ± 0.09</td>
<td>0.18 ± 0.03</td>
<td>0.02 ± 0.02</td>
<td>1.36 ± 0.10</td>
<td>5.58 ± 0.14</td>
</tr>
<tr>
<td>Theory Cross Section [%]</td>
<td>$^{+9}_{-6}$</td>
<td>–</td>
<td>±28</td>
<td>±13</td>
<td>$^{+7}_{-6}$</td>
<td>–</td>
</tr>
<tr>
<td>Luminosity [%]</td>
<td>±2.8</td>
<td>–</td>
<td>±2.8</td>
<td>±2.8</td>
<td>±2.5</td>
<td>±2.8</td>
</tr>
<tr>
<td>Tau trigger [%]</td>
<td>±10</td>
<td>–</td>
<td>&lt; 1</td>
<td>–</td>
<td>±7</td>
<td>±10</td>
</tr>
<tr>
<td>Tau ID [%]</td>
<td>±13</td>
<td>–</td>
<td>±5</td>
<td>±5</td>
<td>±10</td>
<td>±13</td>
</tr>
<tr>
<td>Tau 3-prong [%]</td>
<td>±4</td>
<td>–</td>
<td>&lt; 1</td>
<td>±61</td>
<td>±60</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Jet-to-tau fake-rate [%]</td>
<td>&lt; 1</td>
<td>–</td>
<td>±61</td>
<td>±60</td>
<td>±9</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Tau energy scale [%]</td>
<td>±12</td>
<td>–</td>
<td>±5</td>
<td>–</td>
<td>±9</td>
<td>±2</td>
</tr>
<tr>
<td>Jet energy scale [%]</td>
<td>&lt; 1</td>
<td>–</td>
<td>$^{+1}_{-5}$</td>
<td>–</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [%]</td>
<td>&lt; 1</td>
<td>–</td>
<td>$^{-3}_{+0.2}$</td>
<td>–</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Multijet fake-factor [%]</td>
<td>–</td>
<td>±58</td>
<td>–</td>
<td>–</td>
<td>±7</td>
<td>–</td>
</tr>
</tbody>
</table>