ATLAS searches for heavy resonances

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On behalf of the ATLAS collaboration
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Introduction

ATLAS is carrying out many BSM searches
  - Great to have found the Higgs, but is there more?
  - Many ideas and models

Resonances are an obvious place to look
  - Appear in many models
  - Often dramatic signal on a mundane background
  - Sidebands confirm understanding of Standard Model and detector
  - Figure shows example
    - SSM $Z' \rightarrow ee$
    - Details later

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example_graph.png}
\caption{Example graph showing ATLAS search for $Z' \rightarrow ee$.}
\end{figure}
ATLAS detector

ATLAS 2012
8 TeV \( pp \)
\[ L_{\text{int}} = 20 \text{ fb}^{-1} \]
Searches

The following resonance searches are described here

- Dilepton: $Z' \rightarrow ll$ and other interpretations
- $W' \rightarrow l\nu$
- $W' \rightarrow WZ \rightarrow lll\nu$
- $G^* \rightarrow HH \rightarrow bbbb$
- QBH $\rightarrow lj$ (QBH = quantum black hole)

For more, see the ATLAS public results page

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
Dilepton search

Dilepton search results were recently submitted for publication

- Preliminary $Z' \rightarrow ll$ results were released in March 2013
- New results include many models

Search spectra below

- Left is $ee$, right is $\mu\mu$
- Search variable is the dilepton mass

![Search spectra](image-url)
Dilepton limits

Statistical analysis
- Spectra show no evidence for BSM resonance
- Bayesian analysis done for a fine-grained scan over $m_{ll}$
- For a variety of signals $Z'$ and $Z^*$
  - Classic SSM $Z'$
  - $E_6$ models $Z_\chi$ and $Z_\psi$
    - Weaker and narrower than $Z'$
  - $Z^*$ - tensor coupling
  - SSM $m_{Z'} > 2.9$ TeV

$G^*$ (first KK graviton excitation)
- Limit on coupling vs. mass
- $M_{G^*} > 2.7$ TeV for $\frac{k}{M_{Pl}} > 0.1$
QBH (quantum black hole)
  • Low-scale quantum gravity BH can decay to two objects
  • See later discussion
  • Limits shown as function of threshold mass
    o For both RS and ADD ($n = 6$)

Minimal Walking Technicolor
  • Model is a composite Higgs consistent with present LHC observations
  • Techni-meson decay to $ll$
  • Limits shown as function of coupling and axial-vector mass
$W' \rightarrow l\nu$ search

Lepton + MET resonance search

- **ATLAS-CONF-2014-017**
- Signal is a single high-pT lepton ($e$ or $\mu$)
  - Separate search for each channel
  - Large missing transverse momentum (MET)
- Search performed in transverse mass
  - $m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \varphi_{l\nu})}$
$W'\rightarrow l\nu$ limits

Statistical analysis

- BG estimated from Monte Carlo
- Signal from MC and measurements of electron and muon efficiencies
  - Signal efficiency: 20-40%
  - SSM $W'$
  - Excited chiral boson
- Single-bin Bayesian analysis
  - Variable threshold on $m_T$
- No evidence of signal
- Limits shown in plots
  - Combination of electron and muon channels
  - $m_{W'} > 3.3$ TeV

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Diboson resonances

Many models predict diboson resonances

• GUTs, Little Higgs, Technicolor, composite Higgs, extra dimensions, ...

• SSM Z’ and W’ are often used as benchmarks
  o Also graviton

• ATLAS is carrying out searches in many channels
  o WZ, WW, ZZ, HH, ...

• And there are many decay modes for the bosons
  o W→lv, Z→ll, H→bb, ...

• Report here on two recent results
  o W’→WZ→lllv
  o X→HH→bbbb
W'→WZ→lllv search

Fully-leptonic search for W'

- **ATLAS-CONF-2014-015**
- Lepton = electron or muon
- Z from opposite-sign, same-flavor leptons
  - |m_\ell - m_Z| < 20 GeV
- W from lepton and MET (assumed from neutrino)
  - Neutrino p_z determined from m_{l\nu} = m_W
  - Smallest real or real part of imaginary solution retained
- Search in m_{WZ} in two distinct signal regions
  - Δφ(l, MET) < 1.5 for high mass
    - Inverse for low mass
  - Search boundary at 250 GeV
Statistical analysis

- BG taken from Monte Carlo
- Signal from MC and data-driven estimates of lepton efficiencies and fake rates
  - Signal efficiency shown in plot (6-35%)
- No evidence for signal
- $\text{CL}_S$ evaluation of limits
  - See figure
  - $m_{W'} > 1.5$ TeV
- Limits also set for HVT (heavy vector triplets) with different strength parameters

ATLAS simulation preliminary

ATLAS preliminary

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

Expected 95% CL Limit

- 95% CL $\pm 1\sigma$
- 95% CL $\pm 2\sigma$

Observed Limit

- EGM W'
- HVT A($g=1$)
- HVT A($g=3$)
- HVT B($g=3$)
Di-Higgs search

- With Higgs boson observation, we can now search for decays to Higgs
- Here search for $G^*$ decay to a narrow $HH$ resonance
- Both Higgs decay to $bb$
- Signal is four $b$-jets where each of two distinct $bb$ pairs has mass close to 125 GeV
  - Plus veto of events where extra jets look like top
- Remaining BG is 90% multijet
  - Normalized using control region (i.e. not $HH$ or $ZH$) and comparing with same for 2-tag
- Lower plots shows the search spectrum after selection
**$G^* \rightarrow HH \rightarrow bbb$ limits**

**Statistical analysis**

- Search range 0.5 - 1.5 TeV
- No evidence for signal
- Limits obtained with $\text{CL}_s$
- Signal (first KK excitation of graviton) shape and normalization taken from simulation
- Signal efficiency: 2-6%
- Plot at right shows cross section limits
- Benchmark excluded for $590 < m_{G^*} < 710$ GeV
- **ATLAS-CONF-2014-005**
Quantum black holes (QBHs)
• Predicted in low-scale quantum gravity theories
• With mass near $m_D$, QBH may decay to two particles
  o Unlike semiclassical BHs which decay to many particles
  o $m_D = $ scale of quantum gravity

QBH search
• Search in the lepton-jet ($lj$) channel where BG is small
  o lepton = electron or muon
• Figures show $m_{lj}$
  o Lepton + highest-$p_T$ jet
  o Top is electron channel
  o Bottom is muon channel
QBH→$lj$ limits

Statistical analysis

- BG shapes taken from simulation with normalization obtained from control regions and MET spectra
- Signal depends on assumed threshold mass $M_{th}$
  - Modeling approximations are valid above this value
  - Taken to be equivalent to the inverse gravitational radius
  - The number of signal events is obtained by counting those with $m_{lj}$ above a threshold close to $M_{th}$
    - Difference accounts for detector resolution
- No evidence for signal
- Limits evaluated using CL$_S$
  - Figure at right
    - For n= 6 ADD extra dimensions
      - $M_{th} > 5.3$ TeV
- PRL 112, 091804 (2014)
- Similar search for gamma+jet final state published last year
  - PLB 728, 562 (2013)
Summary and conclusions

ATLAS searches for heavy resonances

• Part of a wide-ranging search for physics beyond the Standard Model
• A few recent searches are reported here
  o These and many earlier searches and other ATLAS results available from ATLAS public results page
  o Expect more results on 2012 data in the coming months
• So far the standard model looks pretty good
  o No BSM observations yet
  o But many limits on BSM signals
  o Chart on following page summarizes these using benchmark signals
    – See papers and public notes for full kinematic limits

Future

• These and other resonance searches will be extended significantly in the upcoming and future runs at the LHC
• ATLAS-PHYS-PUB-2013-003 concludes, in the absence of a signal, the limit for the SSM $Z'$ increases to $m > 7.8$ TeV for 3000 fb$^{-1}$ at 14 TeV
### ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** April 2014

\[ \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1} \]

**\( \sqrt{s} = 7, 8 \text{ TeV} \)**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}^T )</th>
<th>( \mathcal{L} dt \text{[fb}^{-1}] )</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD GKK + ( g/q )</td>
<td>(-1 2 j)</td>
<td>Yes</td>
<td>4.7</td>
<td>( M_{\text{GKK}} )</td>
<td>4.37 TeV</td>
<td>1210.4491</td>
</tr>
<tr>
<td>ADD non-resonant ( \ell \gamma )</td>
<td>(2 \text{ or } 2 \text{e, } \mu)</td>
<td>(-)</td>
<td>4.7</td>
<td>( M_{\text{GKK}} )</td>
<td>4.18 TeV</td>
<td>1211.1150</td>
</tr>
<tr>
<td>ADD QBH ( \rightarrow \ell \ell)</td>
<td>(1 e, \mu)</td>
<td>1 j</td>
<td>20.3</td>
<td>( M_{\text{GKK}} )</td>
<td>5.2 TeV</td>
<td>1311.2006</td>
</tr>
<tr>
<td>ADD BH High ( N_{\mu} )</td>
<td>(2 \mu ) (SS)</td>
<td>(-)</td>
<td>20.3</td>
<td>( M_{\text{GKK}} )</td>
<td>5.7 TeV</td>
<td>1308.4075</td>
</tr>
<tr>
<td>ADD BH High ( \Sigma, \rho T )</td>
<td>(\geq 1 e, \mu \geq 2 j)</td>
<td>(-)</td>
<td>20.3</td>
<td>( M_{\text{GKK}} )</td>
<td>6.2 TeV</td>
<td>1308.4075</td>
</tr>
<tr>
<td>RSL GKK ( \rightarrow t \ell)</td>
<td>(2 e, \mu)</td>
<td>(-)</td>
<td>20.3</td>
<td>( M_{\text{GKK}} )</td>
<td>2.47 TeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>RSL GKK ( \rightarrow Z \ell \ell)</td>
<td>(2 \text{ or } 4 e, \mu)</td>
<td>(2 j \text{ or } -)</td>
<td>1.0</td>
<td>( M_{\text{GKK}} )</td>
<td>845 GeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>RSL GKK ( \rightarrow WW \ell \ell)</td>
<td>(2 e, \mu)</td>
<td>(-)</td>
<td>4.7</td>
<td>( M_{\text{GKK}} )</td>
<td>1.23 TeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>Bulk BS GKK ( \rightarrow HH \rightarrow bb\bar{b})</td>
<td>(-)</td>
<td>4 b</td>
<td>19.5</td>
<td>( M_{\text{GKK}} )</td>
<td>590-710 GeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>Bulk BS GKK ( \rightarrow tt)</td>
<td>(1 e, \mu \geq 1 b, \geq 1 j)</td>
<td>Yes</td>
<td>14.3</td>
<td>( M_{\text{GKK}} )</td>
<td>0.5-2.0 TeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>S1/2 ( z_2) ED</td>
<td>(2 e, \mu)</td>
<td>(-)</td>
<td>5.0</td>
<td>( M_{\text{GKK}} = R^{-1})</td>
<td>4.71 TeV</td>
<td>1293.0718</td>
</tr>
<tr>
<td>UED</td>
<td>(2 \gamma)</td>
<td>(-)</td>
<td>4.8</td>
<td>( \text{Compact}, \text{scale } R^{-1})</td>
<td>1.41 TeV</td>
<td>1293.0718</td>
</tr>
</tbody>
</table>

**Gauge bosons**

|  | \( SSM Z' \rightarrow \ell\ell\) | \(2 e, \mu\) | \(-\) | 20.3 | \( Z'\) mass | 2.86 TeV | ATLAS-CONF-2013-017 |
|  | \( SSM Z' \rightarrow \tau\tau\) | \(2 \tau\) | \(-\) | 19.5 | \( Z'\) mass | 1.9 TeV | ATLAS-CONF-2013-026 |
|  | \( SSM W' \rightarrow \ell\ell\) | \(1 e, \mu\) | \(-\) | 20.3 | \( W'\) mass | 3.28 TeV | ATLAS-CONF-2013-017 |
|  | \( EGM W' \rightarrow WZ \rightarrow \ell\ell\ell'\) | \(3 e, \mu\) | \(-\) | 20.3 | \( W'\) mass | 1.52 TeV | ATLAS-CONF-2013-015 |
|  | \( LHS W'_{Z} \rightarrow t\bar{b}\) | \(1 e, \mu\) | 2 b, 0-1 j | Yes | 14.3 | \( W'\) mass | 1.81 TeV | ATLAS-CONF-2013-050 |

|  | \( Cl \) | qqq | \(-2 j\) | 4.8 | \( \Lambda\) | 7.6 TeV | \( \eta = +1\) | 1210.1178 |
|  | \( Cl \) | q\ell\ell | 2 e, \(\mu\) (SS) \(\geq 1 b, \geq 1 j\) | Yes | 14.3 | \( \Lambda\) | 13.9 TeV | \( \eta_{\ell\ell} = -1\) | 1211.1150 |
|  | \( Cl \) | rtt | \(2 e, \mu, \mu\) | \(-\) | 5.0 | \( \Lambda\) | 3.3 TeV | \( |\eta| = 1\) | ATLAS-CONF-2013-051 |

|  | \( D N J \) | D5 operator | \(-1 2 j\) | Yes | 10.5 | \( M_{\chi}\) | 731 GeV | ATLAS-CONF-2012-147 |
|  | \( D N J \) | D9 operator | \(-1 J, \leq 1 j\) | Yes | 20.3 | \( M_{\chi}\) | 2.4 TeV | ATLAS-CONF-2012-147 |

|  | \( L Q \) | \( L Q 1\text{st} \text{gen}\) | \(2 e\) | \(\geq 2 j\) | 1.0 | \( L Q \) mass | 660 GeV | 1112.4628 |
|  | \( L Q \) | \( L Q 2\text{nd} \text{gen}\) | \(2 \mu\) | \(\geq 2 j\) | 1.0 | \( L Q \) mass | 685 GeV | 1203.3172 |
|  | \( L Q \) | \( L Q 3\text{rd} \text{gen}\) | \(1 e, \mu, 1 r, 1 b, 1 j\) | \(-\) | 4.7 | \( L Q \) mass | 534 GeV | 1303.0560 |

**Heavy quarks**

|  | \( V Q Q \) | \(\rightarrow T T \rightarrow H t + X\) | \(1 e, \mu \geq 2 b, \geq 4 j\) | Yes | 14.3 | \( T\) mass | 790 GeV | ATLAS-CONF-2013-018 |
|  | \( V Q Q \) | \(\rightarrow W W + X\) | \(1 e, \mu \geq 1 b, \geq 3 j\) | Yes | 14.3 | \( T\) mass | 676 GeV | ATLAS-CONF-2013-060 |
|  | \( V Q Q \) | \(\rightarrow Zb + X\) | \(2 e, \mu \geq 2 b\) | \(-\) | 14.3 | \( B\) mass | 725 GeV | ATLAS-CONF-2013-056 |
|  | \( V Q Q \) | \(\rightarrow BB + X\) | \(2 e, \mu, (SS) \geq 1 b, \geq 1 j\) | Yes | 14.3 | \( B\) mass | 720 GeV | ATLAS-CONF-2013-051 |

**Excited lepton**

|  | \( L R S M \) | Majorana | \(1 e, \mu\) | \(2 j\) | \(-2.1\) | \( N^0\) mass | 1.5 TeV | 1203.3172 |

**Other**

|  | \( L R S M \) | Majorana | \(2 e, \mu\) | \(2 j\) | \(-5.8\) | \( N^0\) mass | 245 GeV | 1203.3172 |
|  | \( H g gl\) trapezoid | \( H^0 \rightarrow \ell\ell\) | \(2 e, \mu, (SS)\) | \(-\) | 4.7 | \( H^0\) mass | 409 GeV | 1207.6411 |

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*Only a selection of the available mass limits on new states or phenomena is shown.*

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