Search for high mass scalar resonances in diboson decay modes at 13 TeV by the ATLAS collaboration

Ben Pearson on behalf of the ATLAS collaboration

2016 Phenomenology Symposium
Introduction

• Searches for an extension to the Higgs sector via an additional heavy, CP-even scalar singlet

• Using complete 2015 Dataset!
  – 3.2 fb^{-1} @ 13 TeV

• Many joint efforts between Higgs and Exotics groups yielding a variety of signal interpretations:
  – Scalar/Heavy-Higgs – spin 0
    • Widths from 4 MeV to 15% of m_x
    • Masses from 200 GeV to 3 TeV
  – Heavy Vector Triplet (HVT) – spin 1
  – Graviton – spin 2

*Covered in this talk
*See talk by Samuel Meehan
Outline

• This talk will highlight the most recent results:

<table>
<thead>
<tr>
<th>Process</th>
<th>Final State</th>
<th>Documentation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \rightarrow WW$</td>
<td>$lvqq + lvlv$ Combination</td>
<td>ATLAS-CONF-2016-021</td>
<td>April 2016</td>
</tr>
<tr>
<td>$X \rightarrow ZZ$</td>
<td>$llvv$</td>
<td>ATLAS-CONF-2016-012</td>
<td>March 2016</td>
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<tr>
<td></td>
<td>$llqq$</td>
<td>ATLAS-CONF-2016-016</td>
<td>March 2016</td>
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<td></td>
<td>$vvqq$</td>
<td>ATLAS-CONF-2015-068</td>
<td>December 2015</td>
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<tr>
<td>$X \rightarrow VV$</td>
<td>$qqqq$</td>
<td>ATLAS-CONF-2015-073</td>
<td>December 2015</td>
</tr>
<tr>
<td></td>
<td>Hadronic Combination</td>
<td>...</td>
<td>...coming soon</td>
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<tr>
<td>$X \rightarrow Z\gamma$</td>
<td>$ee\gamma + \mu\mu\gamma + qq\gamma$</td>
<td>ATLAS-CONF-2016-010</td>
<td>March 2016</td>
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<tr>
<td>$X \rightarrow \gamma\gamma$</td>
<td>-</td>
<td>ATLAS-CONF-2016-018</td>
<td>March 2016</td>
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</tbody>
</table>
Some Tools and Methods

• Searches look for peaks in mass distributions
  – Smooth falling SM backgrounds
  – Searches with >1 neutrino use the transverse mass (m_T)

• High mass resonances result in highly boosted decay products
  – Collimated leptons and jets
  – Dedicated vector boson jet (V_{jet}) tagging
    • Both quarks are reconstructed in a single large-R jet
    • Tagger uses jet mass (m_j) and a substructure variable D_2: compatibility with a two-prong structure
    • m_j requirement to be within 15 GeV of m_W/m_Z
    • p_T dependent requirements on D_2 configured to give 50% signal identification efficiency
Search for high-mass scalar resonances in diboson decay modes

- Signals 500 GeV – 3000 GeV
  - Narrow, 5, 10, and 15% widths
- Dominant backgrounds
  - Top (t\bar{t}) and W+jets
    - Normalized using CRs in simultaneous fit
- Fit discriminant $m_{l\nu J}$
  - Using: $m(l\nu) = m(W)$
**Search for high-mass scalar resonances in diboson decay modes**

- **Similar approach to semi-leptonic channel**
  - Dominant bkgs.: top-quark and $WW$ productions $\rightarrow$ use control regions
  - Fit discriminant transverse mass: $m_T = \sqrt{\left(\sqrt{p_T^H}^2 + m_T^2 + E_T^{\text{miss}}\right)^2 - |p_T^H + E_T^{\text{miss}}|^2}$

- **SR split by $N_{\text{jet}}$ (0, 1, ≥2) advantage of different bkg. comp.**
  - Limits also set on VBF production $\sigma \times \text{BR}$
    - For NWA
    - Expect. limit $\sigma_{\text{ggF}} = 0$
    - Obs. limit $\sigma_{\text{ggF}}$ is nuisance parameter
**X → WW Combined**

- ggF combination ($lνlν N_{jet}$ =0,1)
- Maximum-likelihood fit (SR and CRs)
- No excess $→$ set limits $σ \times BR$
- $lνqq$ dominates in entire mass range
- Significantly expanded the mass range from Run 1 (8 TeV data)
  - JHEP01(2016)032

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**Search for high-mass scalar resonances in diboson decay modes**

- Ben Pearson
- Run 1
  - $ggF$ combination ($lνlν N_{jet}$ =0,1)
  - Maximum-likelihood fit (SR and CRs)
  - No excess $→$ set limits $σ \times BR$
  - $lνqq$ dominates in entire mass range
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Important backgrounds
- ZZ, WZ, Z+jets, and less so WW, tt, Wt, and Z→ττ
- 3-lepton CR for WZ normalization
- eμ CR for inclusive estimate of WW, tt, Wt, and Z→ττ processes

Discriminant: $m_T^{ZZ} = \sqrt{\left(\sqrt{m_2^2 + |p_T^{ll}|^2} + \sqrt{m_2^2 + |E_T^{miss}|^2}\right)^2 - |p_T^{ll} + E_T^{miss}|^2}$

<table>
<thead>
<tr>
<th>Variables</th>
<th>Cut Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton $p_T$ (leading, subleading)</td>
<td>&gt; (30 GeV, 20 GeV)</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>&gt; (30 GeV, 20 GeV)</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>76–106 GeV</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>&gt; 120 GeV</td>
</tr>
<tr>
<td>$\Delta \phi(p_T^{ll}, E_T^{miss})$</td>
<td>&lt; 1.8</td>
</tr>
<tr>
<td>Fractional $p_T$ difference</td>
<td>&gt; 2.7</td>
</tr>
<tr>
<td>Number of $b$-jets</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$\Delta \phi(E_T^{miss}, \text{jets})$</td>
<td>0</td>
</tr>
<tr>
<td>$p_T^{ll}/m_T^{ZZ}$</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>$p_T^{ll}/m_T^{ZZ}$</td>
<td>&lt; 0.7</td>
</tr>
</tbody>
</table>
• The number of data points and the $m_T^{ZZ}$ distributions are consistent with the SM predictions

• Upper limits are set on the $\sigma \times BR$ for NWA
  • For each mass point (300-1000 GeV)
\(X \rightarrow ZZ \rightarrow llqq\)

- Merged and resolved reconstruction of the \(Z \rightarrow qq\) decay
  - Merged: one \(Z\)-tagged large-\(R\) jet (J) and resolved: a pair of small-\(R\) jets (jj)
- Events failing merged analysis selection are “recycled” to resolved
- Resolved analysis further categorization
  - \(b\)-tagged jets: exactly 2 (tagged) and < 2 (untagged)
- Dominant bkgs.: \(Z+\)jets, diboson, top
- Control regions: Top CR for resolved tagged region (diff. flavor \(l\) ’s & \(m_{bb} \approx m_{top}\))
  
  - \(Z+\)jets CR for each signal region (\(m_{J/jj}\) side-bands)

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**Event Recycling**

- Merged
- Resolved Untagged
- Resolved Tagged

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Search for high-mass scalar resonances in diboson decay modes
**X→ZZ→llqq**

- The three signal regions and four CRs are fit simultaneously
  - Constraining the normalization of the Z+jets and Top backgrounds
  - Discriminant is the full invariant mass $m_{llJ} / m_{lljj}$

- No significant excess is observed

- Upper limits are set on the $\sigma \times \text{BR}$ for NWA and LWA
  - For each mass point (300-1000 GeV) and width (NWA & 5,10,15%)
X→ZZ→vvqq

- Dominant bkgs: Z+jets, W+jets, and ttbar
  - Normalized using dedicated control regions in a combined fit
- Fit discriminant transverse mass: \[ m_T = \sqrt{\left(\sqrt{m_j^2 + p_T^2} + E_T^{\text{miss}}\right)^2 - p_T^2 + E_T^{\text{miss}}^2} \]
- Signal region: lepton veto, MET>250 GeV, Z-tagged large-\(R\) jet, 0 b-jets
Search for high-mass scalar resonances in diboson decay modes

- Although G* signal is shown above, results below use scalar signal
- No significant excess observed, so combined limits set on $\sigma \times BR$
$X \rightarrow Z\gamma$, $Z \rightarrow ee, \mu\mu, qq$

- Search for localized excess in the invariant mass distribution
- Leptonic ($ll\gamma$) and hadronic ($J\gamma$) analyses
  - $l = e, \mu$ and $J = \text{large-}R\ \text{jet}$
- **Dominant Bkgs.**
  - Leptonic
    - $Z+\gamma$ continuum
  - Hadronic
    - $\gamma+\text{jet}$ non-resonant SM production
- **Discriminant**
  - Invariant mass $m_{ll\gamma}/m_{J\gamma}$
\[ \mathbf{X \rightarrow Z \gamma} , \mathbf{Z \rightarrow ee, \mu \mu, qq} \]

- Signals $\Gamma_X = 4$ MeV ($m_X = 200$-3000 GeV)
  - **Leptonic Sel**: $p_T(\gamma) > 0.3 m_{ll \gamma}$, and $m_{ll} = m_Z \pm 15$ GeV
  - **Hadronic Sel**: $p_T(\gamma) > 250$ GeV, $Z$-tagged $p_T(J) > 200$ GeV

- Total background exhibits smoothly falling mass spectrum
  - Parameterized by smooth function with data-adjusted parameters

- Maximum-likelihood fit to $m_{ll \gamma} / m_{J \gamma} \rightarrow$ limits on the $\sigma x$ BR

**ll\gamma**: 382 events

**J\gamma**: 534 events
• **Signals** $m_X = 200 - 2000$ GeV
  - Widths ($\Gamma_X$) up to $\Gamma_X/m_X = 10%$
    • Including a narrow width: 4 MeV
    • Large width generation for $m_X \pm 2\Gamma_X$
      - Reduce model effects from off-shell region
  - $m_{\gamma\gamma}$ experimental resolution modelled by a DSCB function

• **Selection:**
  - Diphoton trigger: $E_T > 35(25)$ GeV
    • leading (sub-leading) photon
  - 2 identified and isolated photons
    • With $E_T > 40(30)$ GeV
  - $E_T/m_{\gamma\gamma} > 0.4(0.3)$
• **Background estimation**
  
  - $\gamma\gamma$ QCD from MC
  - $\gamma$+jet and dijet from CRs
  - $m_{\gamma\gamma}$ distribution shape
    
    • Functional form:
      
      \[ f = (1 - x^{1/3})^b x^a \]
    
    - $b$ and $a$ determined by data
    - $x = m_{\gamma\gamma}/\sqrt{s}$

  
  • **Maximum-likelihood fits**
    
    - Entire mass spectrum is used for each mass hypothesis
    - B-only to S+B likelihood ratios for local significances

  
  **2878 events ($m_{\gamma\gamma} > 200$ GeV)**

  
  ![Graph showing ATLAS Preliminary data with background-only fit](image)

  
  ATLAS Preliminary
  
  - Data
  - Background-only fit
  
  Spin-0 Selection
  
  $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
Search for high-mass scalar resonances in diboson decay modes

- Largest deviation observed around $m_X = 750$ GeV
  - $3.9\sigma$ (2\sigma global) with a $\Gamma = 45$ GeV (6\%) signal width
  - Global significance accounts for look-elsewhere-effect using pseudo-experiments

- Not enough for discovery, so limits on $\sigma_{\text{fid}}$ evaluated
  - Fiducial cross-section to minimize model dependence

\[ \frac{\Gamma}{m_X} [\%] \]

\[ \sigma_{\text{fid}} \times \text{BR} [\text{fb}] \]

\[ m_X [\text{GeV}] \]

\[ \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]

\[ \Gamma_{\chi}/m_{\chi} = 6 \% \]

\[ \text{Spin-0 Selection} \]

\[ \text{Fiducial} \text{ cross-section to minimize model dependence} \]
Summary and Outlook

- Just the tip of the iceberg!?
- Eager for **more data!**
  - May have 6-8 fb\(^{-1}\) by ICHEP and >20 fb\(^{-1}\) by the end of the year
- Collaboration is working hard to output results as efficiently as possible
- Always room for improvement
  - Large-\(R\) jet systematics dominate most hadronic channels
  - Improvements to large-\(R\) jet mass resolution in progress
- The future is bright! Bring on the lumi!
Backup Material
• Comparison with 8 TeV data

• 20 fb\(^{-1}\) reanalyzed data
  – Newest 8 TeV photon energy calibration
  – Same ID and isolation
  – Extended mass range

• 750 GeV and 6% = \(\Gamma/m_X\)

  signal hypothesis

  – Excess of 1.9\(\sigma\) @ 750 GeV
  – Difference between 8 and 13 TeV results corresponds to a statistical significance of 1.2\(\sigma\) (2.1\(\sigma\)) for gg(qq) production
• Limits for other widths:

- Observed $CL_s$ limit
- Expected $CL_s$ limit
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
$\Gamma_X/m_X$ = 1 %
Spin-0 Selection

$95\%$ CL Upper Limit on $\sigma_{id} \times$ BR [fb]

- ATLAS Preliminary
- Observed $CL_s$ limit
- Expected $CL_s$ limit
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

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- ATLAS Preliminary
- Observed $CL_s$ limit
- Expected $CL_s$ limit
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

$95\%$ CL Upper Limit on $\sigma_{id} \times$ BR [fb]
• Limit for a narrow width 4 MeV signal (previous CONF note)
• Kinematic distribution sanity checks:
• Double-sided Crystal Ball function:

\[ X \rightarrow \gamma \gamma \]

![Graph showing ATLAS search for high-mass scalar resonances in diboson decay modes]

- Gaussian Distribution
- Power Law: \[ \sim (-m_{\gamma \gamma})^{-\eta_{\text{Low}}} \]
- Power Law: \[ \sim (m_{\gamma \gamma})^{-\eta_{\text{High}}} \]
- \( \Delta m_X \)
• **Control regions:**
  
  – Top CR for resolved tagged region (diff. flavor $l$’s & $m_{bb} \approx m_{top}$)
  
  – Z+jets CR for each signal region ($m_{jj}$ side-bands)

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