Searches for di-boson resonances in ATLAS

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on behalf of the ATLAS Collaboration
Theoretical Framework

- **Heavy Vector Triplet**
  - arXiv:1402.4431v2
  - Effective Lagrangian with additional fields $V^{+,0,-}$.
  - Can tune mass, couplings to fermions and bosons.
  - Two benchmark scenarios
    - **A**: extended gauge symmetry
    - **B**: minimal composite higgs model
Theoretical Framework

- “bulk” RS graviton with warped extra dimension
- Extension of KK graviton in RS1 framework with SM particles extending into the “bulk”.
- Couplings to light fermions suppressed.
- $gg$ fusion dominant production channel.
- High BR of $G^* \rightarrow VV$. 
Di-boson channels

- Di-boson searches in ATLAS
  - $V V \rightarrow q q q q$, $W V \rightarrow l v q q$, $Z V \rightarrow l l q q$, $v v q q$
  - $W Z \rightarrow l v l l$, $Z Z \rightarrow l l l l$
  - $V H \rightarrow q q b b$, $l v b b$, $v v b b$
  - $H H \rightarrow b b b b, b b \gamma \gamma, \gamma \gamma l v j j$
  - $Z \gamma \rightarrow l l \gamma$, $q q \gamma$
  - $\gamma \gamma$
  - $H' \rightarrow W W \rightarrow l v l v$
  - $H' \rightarrow Z Z \rightarrow l l l l$

Focus on latest 2015+2016 data-set analyses!
Techniques

- Search for **narrow** resonances
  - Look for peak in invariant mass spectrum over a smooth background.
  - Experimental mass resolution typically few percent for hadronic decays.
  - Use test statistics for hypothesis testing and derive limits on production cross section times branching ratio.

- **Final states**
  - semi-leptonic and hadronic.
    - High BR and acceptable mass resolution.
  - Fully leptonic
    - High mass resolution.
Techniques

- Boosted hadronically decaying bosons.
  - Large R jets

- Boosted leptonically decaying bosons.
  - Isolation cone variations.
  - Di-lepton isolation.

*ATLAS Simulation*
- $gg \rightarrow X \rightarrow Z\gamma$
- $\sqrt{s}=13$ TeV
- $m_X=200$ GeV
- $m_X=300$ GeV
- $m_X=500$ GeV
- $m_X=1000$ GeV
- $m_X=1500$ GeV
- $m_X=2000$ GeV

Alexander Oh, LHCP 2017
Techniques

Large R jet grooming:

Improve mass resolution by suppressing soft contributions from pile-up underlying event.

(D. Krohn, J. Thaler, L. Wang)

- uses $k_t$ algorithm to create subjets of size $R_{Sub}$ from the constituents of the large-R jet:
  any subjets failing $p_T^{i} / p_T^{jet} < f_{cut}$ are removed

Tuned parameters: $f_{cut}$ and $R_{Sub}$


- Recombine jet constituents with C/A or kt while vetoing wide angle ($R_{cut}$) and softer ($z_{cut}$) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

Tuned parameters: $R_{cut}$ and $z_{cut}$

Emily Thompson, BOOST2012
Techniques

- **W/Z boson tagging** for merged events
  - Require mass
    - Consistent with Z or W within ±15 GeV).
    - [H->qqbb] $p_T$ dependent window, masss computed from calo and tracking information.
  - “D2” substructure variable consistent with 2 prong decay.

- **Higgs boson tagging**
  - Use anti-kT R=0.2 track jets and b-tagging.
VV: qqqq

- VV searches in hadronic final state, \( L=15.5 \text{ fb}^{-1} \).
  - Only merged regime, both hadronically decaying V’s reconstructed as large-R jet.
    - Boson tagged large R-jets.
  - QCD rejection
    - Number of tracks associated
      \( N_{\text{trk}} < 30 \).
    - \( |DY_{JJ}| < 1.2 \)
    - \( (P_{T,1} - P_{T,2}) / (P_{T,1} + P_{T,2}) < 0.15 \)
- Main background QCD
  - Data driven
  - Double polynomial for shape
  - Validation in sidebands (jet mass)
**VV**: qqqq

- Tested WW, WZ and ZZ signal regions.
- No significant excess found.
- Largest deviation 1.9 $\sigma$ local in HVT $W'$ to WZ hypothesis with $m(W')=1.9\text{TeV}$.
- 95% CL limits set:
  - $[1.2\text{ TeV}, 1.9\text{ TeV}]$ $W'$, $g_\nu=1$
  - $3.0\text{ TeV}$ $W'$, $g_\nu=3$
  - $1.8\text{ TeV}$ $Z'$, $g_\nu=1$
  - $1.9\text{ TeV}$ $Z'$, $g_\nu=3$
VH: qqbb

- **V-> qq, H-> bb** final state, **36.1 fb⁻¹**.
  - Large branching ratio but high QCD background.
  - Complementary to semi-leptonic channels.
  - Sensitive to highest mass region (low background).

- **Only merged regime**
  - Require two large-R jets, tagging H (higher mass) and V (lower mass) in combined tagging algorithm.
  - “Combined jet mass” from calorimetric and track assisted measurements to improve resolution.
VH: qqbb

- **Main Background QCD**
  - Data driven with side-band sample
    - 0 b-tag, reweighted for kinematic differences.
  - Normalization fixed with H-jet sideband ($145 \text{ GeV} < m(H_{\text{jet}}) < 200 \text{ GeV}$).
  - Modeling checked with validation region.

- Sub-leading backgrounds $t\bar{t}$, $V+$jets.
VH: qqbb

- Largest deviation in ZH channel
  - local $3.3\sigma$, global $2.2\sigma$
  - $M(JJ) \sim 3.0$ TeV

<table>
<thead>
<tr>
<th>95% CL exclusion</th>
<th>$M_{WH}$ [GeV]</th>
<th>$M_{ZH}$ [GeV]</th>
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</thead>
<tbody>
<tr>
<td>HVT Model A ($g_v=1$)</td>
<td>1100-2400</td>
<td>1100-1480; 1700-2350</td>
</tr>
<tr>
<td>HVT Model B ($g_v=3$)</td>
<td>1100-2500</td>
<td>1100-2600</td>
</tr>
</tbody>
</table>
H → WW → ℓννv, 13.2 fb⁻¹.
- ggF and VBF categories
- eνμν final state to suppress backgrounds from DY.
- Discriminating variable transverse mass m_T:

\[ m_T = \sqrt{(E_T^{ℓν} + E_T^{miss})^2 - p_T^{ℓν} + E_T^{miss}} \]

- Signal regions
  - ggF
  - VBF 1j, 2j

- Background
  - Dominant WW and top backgrounds.
  - Use control region to constrain normalization.

- No significant excess.
  - Limits for narrow, and 5%, 10%, 15% width models.
H ZZ

- H -> ZZ -> llll, 14.8 fb⁻¹.
  - e and mu final state.
  - Z mass constraint on both Z candidates to improve mass resolution by 15%.

- Signal regions
  - inclusive
  - ggF
  - VBF

- Background
  - Dominant ZZ* from MC
  - Z+jets and tt from data driven methods.

- No significant excess.
  - Limits for narrow, and 1%, 10%, 15% width models.
$Z\gamma: \gamma\gamma$

- Full 2015+2016 data set of 36.1 fb$^{-1}$
  - Update to previous result with 13.3 fb$^{-1}$ (ATLAS–CONF–2016–044)

- **Selection**
  - $Z$ candidate $|M(Z) - m(\ell\ell)| < 15$GeV, ee and $\mu\mu$ final states.
    - Apply kinematic fit to improve the mass resolution.
  - $\gamma$ candidate “tight” id and isolation, including conversion.
  - Select $\gamma$ with highest $p_T$.
  - Categorize events into ee and $\mu\mu$.
  - Experimental Signal resolution ~1%.
$Z\gamma: \Pi\gamma$

- Signal:
  - Modeled with double-sided Crystal Ball function.
  - Efficiency 20%-50% depending on mass and signal model.
- Dominant background $Z+\gamma$ and $Z+jets$.
- Composition of background from data.
- Background shape modeled analytically.
Zγ: llγ

- No significant excess found.
- Largest deviation $2.7\sigma$ local, $0.9\sigma$ global at $m(Z\gamma) = 960\text{GeV}$.
- Dominated by muon channel.
- Set limits for spin-0 and spin-2 resonances.
Wrap-up

- Run-2 results with full 2015+2016 data sample are getting ready.
- Mass reach profits from higher statistics.
- Advance tagging technics help to effectively reject QCD background.
- No significant excess observed in most channels.
- Waiting for more data!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi</th>
<th>Documentation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV: qqqq</td>
<td>15.5</td>
<td>ATLAS-CONF-2016-055</td>
<td>03.08.16</td>
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<tr>
<td>HV-&gt;qqbb</td>
<td>36</td>
<td>ATLAS-CONF-2017-018</td>
<td>21.03.17</td>
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<td>h-&gt;zz -&gt; llll</td>
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<td>ATLAS-CONF-2016-079</td>
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<td>h-&gt;ww-&gt;lvlv</td>
<td>13.2</td>
<td>ATLAS-CONF-2016-074</td>
<td>04.08.16</td>
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<td>h-&gt;Zgam</td>
<td>36.1</td>
<td>HIGG-2016-14 (plots)</td>
<td>14.05.17</td>
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