Searches for Heavy Resonances Decaying to a W or Z Boson and a Higgs Boson with the ATLAS experiment

Inês Ochoa

DPF 2017
July 31 - August 4, 2017
• A solution to the **naturalness problem**:
  • New physics at the TeV energy scale, reachable at the LHC.
  • BSM models typically predict new heavy vector resonances: \( W' \) and \( Z' \).

• **Heavy vector resonances**:
  • \( W' \) and \( Z' \) can be expected to couple to \( W/Z \) and Higgs bosons.
  • Results can be interpreted in the context of a simplified model with additional SU(2) vector triplet: Heavy Vector Triplet (HVT) \( V' \).  
  
  **JHEP09(2014)060**

• In this talk: ATLAS searches in the WH and ZH decay channels.
  • Using 2015+2016 dataset with a luminosity of 36.1 fb\(^{-1}\) at \( \sqrt{s} = 13 \) TeV.
  • 2HDM interpretation also included for neutral resonances: not covered here.

⇒ Introduction to Heavy Vector Triplets in C. Vernieri’s talk.
Different analyses target different **W and Z boson decays** and the **Higgs boson** decay to a pair of b-quarks:

- The largest branching fraction of the Standard Model Higgs, of ~60%.
- Suite of analyses built such that there is no event overlap.
Search strategy

- Resonance mass range covered: from 500 GeV to 5 TeV!
- Boost of the decay products will depend on the mass of the new resonance.
- Two regimes are targeted for the Higgs reconstruction:

**Bump search:** the search strategy is to scan the invariant or transverse mass distributions of WH and ZH for evidence of a resonant excess.
The Higgs boson as a discovery tool

- **Invariant mass** of large-R jet or di-jet system compatible with Higgs boson mass.
  - Mass resolutions improved by correcting for semi-leptonic decays of the b-hadrons.
  - Large-R jets further improved at high momentum by combining calorimeter and tracking information:
    \[
    m_J \equiv w_{\text{calo}} \times m_{J}^{\text{calo}} + w_{\text{track}} \times \left( m_{J}^{\text{track}} \frac{p_{T}^{\text{calo}}}{p_{T}^{\text{track}}} \right)
    \]
- **b-tagging**: at least one b-tagged (track-)jet associated with the Higgs jet.
  - Events with only one b-tag are crucial at high boosts, as track-jets start merging.

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**ATLAS** Simulation Preliminary

- **Large-R jet mass**
- **ATLAS Simulation**
  - 2-tag SR (WH)
  - 1-tag SR (WH)
  - 2-tag SR (ZH)
  - 1-tag SR (ZH)

**ATL-PHYS-PUB-2015-035**

arXiv:1707.06958
V'→VH in the all-hadronic final state

- Profits from the large branching ratios of W/Z to quarks.
  - $\text{BR}(W\rightarrow q\bar{q}') \sim 67\%$ and $\text{BR}(Z\rightarrow q\bar{q}) \sim 69\%$

- Only boosted scenario is considered for this final state:
  - Two large-R jets required in the event: higher mass jet is assigned as Higgs candidate.

- Multijet QCD processes are the main background to this search (>90%).
  - Strong rejection coming from W/Z and Higgs jet substructure cuts and $b$-tagging.
  - Can’t rely on simulation: large cross-sections coupled with low background efficiencies.
  - A data-driven method is used instead.
  - Top-pair and V+jets estimated from simulation.

Higgs-tagging:
- $75 < m_J < 145$ GeV
- $b$-tagging @ 77% efficiency
- W/Z-tagging at 50% efficiency:
  - $p_T$-dependent mass window
  - $p_T$-dependent $D_2$ selection (two-prong decay structures)

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V'→VH in the all-hadronic final state

- Signal regions:
  - 2 channels depending on mass of vector-boson candidate: WH or ZH.
  - 1-tag and 2-tag categories for the #b-tagged jets associated with Higgs jet.

- Background estimation:
  1. Extract template from region with 0-tags and normalization from high-mass sidebands of the “Higgs”.

\[
\mu_{\text{Multijet}}^{1(2)-\text{tag}} = \frac{N_{\text{Multijet}}^{1(2)-\text{tag}}}{N_{\text{Multijet}}^{0-\text{tag}}} = \frac{N_{\text{data}}^{1(2)-\text{tag}} - N_{t\bar{t}}^{1(2)-\text{tag}} - N_{V+\text{jets}}^{1(2)-\text{tag}}}{N_{\text{data}}^{0-\text{tag}} - N_{t\bar{t}}^{0-\text{tag}} - N_{V+\text{jets}}^{0-\text{tag}}}
\]

\(\text{Higgs boson candidate mass [GeV]}\)

\(\text{Number of b-tags}\)

- 0-tag “SR” sideband
- 1-tag SR sideband
- 2-tag SR sideband

arXiv:1707.06958
**V'→VH** in the all-hadronic final state

- **Signal regions:**
  - **2 channels** depending on mass of vector-boson candidate: WH or ZH.
  - **1-tag and 2-tag categories** for the #b-tagged jets associated with Higgs jet.

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  1. Extract template from region with **0-tags** and normalization from **high-mass sidebands** of the “Higgs”.
  2. Correct 0-tag template using variables correlated with b-tagging efficiency and heavy quark content.

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arXiv:1707.06958
V'→VH in the all-hadronic final state

- **Signal regions:**
  - **2 channels** depending on mass of vector-boson candidate: WH or ZH.
  - **1-tag and 2-tag categories** for the #b-tagged jets associated with Higgs jet.

- **Background estimation:**
  1. Extract template from region with **0-tags** and normalization from **high-mass sidebands** of the “Higgs”.
  2. Correct 0-tag template using variables correlated with b-tagging efficiency and heavy quark content.
  3. Validation and shape uncertainties in multi-jet from **validation regions**.

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arXiv:1707.06958
V'→VH in the all-hadronic final state

- A likelihood fit with the 1-tag and 2-tag signal regions.
- Largest experimental uncertainties from jet mass resolution, jet energy scale and b-tagging efficiencies.
- Largest excess at a mass of ~3 TeV with a local (global) significance of 3.3 (2.1) σ.
- Cross-section limits derived for W’ and Z’ production. Exclusions for Model B:
  - m_{w'} < 2.5 TeV and m_{Z'} < 2.6 TeV
- WH cross-section limits and signal regions shown in backup slides. Note: WH/ZH overlap by ~60%.
**V’→VH in the all-hadronic final state**

- A likelihood fit with the 1-tag and 2-tag signal regions.
- Largest experimental uncertainties from jet mass resolution, jet energy scale and b-tagging efficiencies.
- Largest excess at a mass of \(\sim 3\) TeV with a local (global) significance of 3.3 (2.1) \(\sigma\).
- Cross-section limits derived for W’ and Z’ production. Exclusions for Model B:
  - \(m_{W'} < 2.5\) TeV and \(m_{Z'} < 2.6\) TeV
- WH cross-section limits and signal regions shown in backup slides. **Note:** WH/ZH overlap by \(\sim 60\%\).

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**Graphs and Tables**

**Observed limit vs. Expected limit**

- ATLAS \(\sqrt{s} = 13\) TeV \(L = 36.1\) fb\(^{-1}\)

**ZH Analysis**

- Observed limit
- Expected limit \(\pm 1\) \(\sigma\)
- Expected limit \(\pm 2\) \(\sigma\)
- HVT Model B, \(g_v = 3\)
- HVT Model A, \(g_v = 1\)

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**Columbia University**

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**arXiv:**[1707.06958](https://arxiv.org/abs/1707.06958)
V'→VH in semi-leptonic final states

• Signal regions:
  • **Merged and resolved** categories.
  • **3 (orthogonal) channels** based on W/Z decay:
    • 0, 1 or 2-leptons.
  • **2 lepton flavor channels**: electron and muon decays.
  • **1-tag and 2-tag categories** for the #b-tagged jets associated with Higgs jet.

• **Backgrounds**: main contributions from top-pair and V+jets production, with varying contributions depending on lepton channel.

• Transition regime (~ 1 TeV) where events can be reconstructed in both the resolved and merged strategies.
  • **Prioritizing the resolved category** leads to better sensitivity due to better mass resolution.
V'\rightarrow VH in semi-leptonic final states

- Shape of most backgrounds estimated from simulation with normalizations of main backgrounds estimated from data.
- Largest backgrounds can be constrained in dedicated control regions:
  - e.g. a 90% pure top-pair region is defined using resolved events with different flavor (e\mu) and oppositely charged leptons.
- A combined fit is performed to all signal and control regions.
- Largest systematic uncertainties from small and large-R jet energy scales, large-R mass scales and b-tagging efficiencies.
V'→VH in semi-leptonic final states

- No significant excess is observed in any channel.
- Cross-section limits derived for:
  - W' (0+1 lepton)
  - Z' (0+2 lepton)
  - HVT model assuming simultaneous production of mass-degenerate W' and Z' bosons
- Exclusions for Model B:
  - \( m_{W'} < 2.9 \text{ TeV} \) and \( m_{Z'} < 2.8 \text{ TeV} \)

\[ \text{V'→VH in semi-leptonic final states} \]

\[ 95\% \text{ C.L. limit} \]

\[ \text{ATLAS Preliminary} \]

\[ \sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1} \]

\[ \sigma(pp \rightarrow V'H)\text{BR}(h \rightarrow b\bar{b},cc) \text{ [pb]} \]

\[ m_{W'} \text{ [GeV]} \]

\[ \text{V'→VH} \]

\[ \text{ATLAS-CONF-2017-055} \]
• Searches in diboson final states are a powerful tool for probing physics at the TeV scale.
• The VH channels are part of a large effort in diboson resonance searches at ATLAS.
  • A combination of the VH/VV channels is expected before the end of the year.

Stay tuned for more LHC data!

A high mass event from the all-hadronic VH analysis:

\[ m_{VH} = 3023 \text{ GeV} \]
Backup slides
Combined plots

**W'→WH**

**Z'→ZH**

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

95% C.L. exclusion limits

- Observed
- Expected
- qqbb
- lvbb

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

95% C.L. exclusion limits

- HVT model \( B \ g = 3 \)
- Observed
- Expected
- qqbb
- llbb
- vvbb

**Link to Exotics Summary plots**

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Jet trimming

Jet mass [GeV]

Arbitrary units

**ATLAS Simulation**
anti-\(k_t\) LCW jets, 600 ≤ \(p_T^{\text{jet}}\) < 800 GeV

- Ungroomed \(Z'\rightarrow \bar{t}t\)
- Ungroomed Dijets
- Trimmed \(Z'\rightarrow \bar{t}t\)
- Trimmed Dijets

JHEP 1309 (2013) 076
Jet mass

**ATLAS Simulation Preliminary**

$\sqrt{s} = 13$ TeV, $WZ \rightarrow qqqq$

anti-$k_t$, $R = 1.0$ jets, $|\eta| < 2.0$

Trimmed ($t_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$)

LCW + JES + JMS calibrated

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**ATLAS-CONF-2016-035**

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Jet substructure

- The $D_2^{\beta=1}$ variable is useful in identifying jets with two-prong substructures.
- Defined from n-point energy correlation functions:

\begin{align*}
E_{CF1}(\beta) &= \sum_{i \in J} p_T^{i}, \\
E_{CF2}(\beta) &= \sum_{i < j \in J} p_T^i p_T^j (\Delta R_{ij})^\beta, \\
E_{CF3}(\beta) &= \sum_{i < j < k \in J} p_T^i p_T^j p_T^k (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^\beta,
\end{align*}

\[ D_2^{\beta=1} = E_{CF3} \left( \frac{E_{CF1}}{E_{CF2}} \right)^3 \]

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ATLAS Simulation
$\sqrt{s}=8$ TeV
$|\eta|^{\text{Truth}} < 1.2$
$500 < p_T^{\text{Truth}} < 1000$ GeV
M Cut
anti-$k_t$ $R=1.0$ jets
Trimmed ($f_{\text{cut}}=5\%, R_{\text{sub}}=0.2$)

EPJC 76(3), 1-47
Flavor tagging

- A multivariate tagging algorithm combines information from vertexing and impact parameter tagging algorithms to a set of tracks associated to a jet/track-jet, in order to identify jets containing b-hadrons.
# Event selections

## All-hadronic VH

<table>
<thead>
<tr>
<th>Selection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton veto</td>
<td>Remove events with leptons</td>
</tr>
<tr>
<td>&gt; 1 large-$R$ jets</td>
<td>$p_T &gt; 250$ GeV, $</td>
</tr>
<tr>
<td>Leading large-$R$ jet $p_T$</td>
<td>$&gt; 450$ GeV</td>
</tr>
<tr>
<td>V/H assignment</td>
<td>larger mass jet is $H$-jet, smaller mass jet is $V$-jet</td>
</tr>
<tr>
<td>Rapidity difference</td>
<td>$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ veto</td>
<td>Remove events with $E_T^{\text{miss}} &gt; 150$ GeV and $\Delta \phi(E_T^{\text{miss}}, H - \text{jet}) &gt; 120$ degrees</td>
</tr>
<tr>
<td>Higgs tagging</td>
<td>mass window, track-jet b-tagging</td>
</tr>
<tr>
<td>W/Z-tagging</td>
<td>mass window + $D^s_{3=1}$ selection</td>
</tr>
<tr>
<td>Dijet mass</td>
<td>$m_{JJ} &gt; 1$ TeV</td>
</tr>
</tbody>
</table>

*arXiv:1707.06958*
Event selections
All-hadronic VH

V boson candidate mass [GeV]

≈110

SR

sideband

≈65

VR-SR

VR-SB

Higgs boson candidate mass [GeV]

0 75 145 200

≈50

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arXiv:1707.06958
Validation regions
All-hadronic VH

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arXiv:1707.06958
Validation regions
All-hadronic VH

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

ATLAS

VR-SB 1-tag

Data
Multijet
Other Backgrounds
Stat. Uncertainty

VR-SB 2-tag

Data
Multijet
Other Backgrounds
Stat. Uncertainty

\( m_{JJ} [\text{GeV}] \)

\( \text{Events / 100 GeV} \)

\( \text{Data / Pred.} \)

arXiv:1707.06958
WH signal regions
All-hadronic VH

\[ W' \rightarrow WH \]

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV} \quad 36.1 \text{ fb}^{-1} \]

1-tag WH

\[
\begin{align*}
\text{Data} & \quad \text{HVT Model B W' (2 TeV) x 50} \\
\text{Multijet} & \\
\text{Other Backgrounds} & \\
\text{Pre-fit} & \\
\text{Uncertainty} & \end{align*}
\]

\[
\begin{align*}
\text{Events / 100 GeV} & \\
10^{-1} & \\
10^{-2} & \\
10^{-3} & \\
10^{-4} & \\
10^{-5} & \\
10^{-6} & \\
10^{-7} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Data / Pred.} & \\
1000 & \\
2000 & \\
3000 & \\
4000 & \\
\end{align*}
\]

2-tag WH

\[
\begin{align*}
\text{Data} & \quad \text{HVT Model B W' (2 TeV) x 50} \\
\text{Multijet} & \\
\text{Other Backgrounds} & \\
\text{Pre-fit} & \\
\text{Uncertainty} & \end{align*}
\]

\[
\begin{align*}
\text{Events / 100 GeV} & \\
10^{-1} & \\
10^{-2} & \\
10^{-3} & \\
10^{-4} & \\
10^{-5} & \\
10^{-6} & \\
10^{-7} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Data / Pred.} & \\
1000 & \\
2000 & \\
3000 & \\
4000 & \\
\end{align*}
\]

arXiv:1707.06958
WH limits
All-hadronic VH

\[ \text{ATLAS} \]
\[ \sqrt{s} = 13 \text{ TeV} \quad 36.1 \text{ fb}^{-1} \]

- Observed limit
- Expected limit ±1 σ
- Expected limit ±2 σ
- HVT Model B, \( g_v = 3 \)
- HVT Model A, \( g_v = 1 \)

arXiv:1707.06958
## Events selections
### Semi-leptonic VH

<table>
<thead>
<tr>
<th>variable</th>
<th>Resolved</th>
<th>Merged</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common selections</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of jets</td>
<td>$\geq 2$ small-$R$ jets (==2 or 3 1-lep.)</td>
<td>$\geq 1$ large-$R$ jet</td>
</tr>
<tr>
<td>leading jet $p_T$ [GeV]</td>
<td>$&gt; 45$</td>
<td>$&gt; 250$</td>
</tr>
<tr>
<td>$m_{jj}$, $m_J$ [GeV]</td>
<td>110–140 (0,1-lep.), 100–145 (2-lep.)</td>
<td>75–145</td>
</tr>
<tr>
<td><strong>0-lepton selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>$&gt; 150$</td>
<td>$&gt; 200$</td>
</tr>
<tr>
<td>$\sum p_T^{jet_i}$ [GeV]</td>
<td>$&gt; 150 (120^{(*)})$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta\phi(j, j)$</td>
<td>$&lt; 7\pi/9$</td>
<td>-</td>
</tr>
<tr>
<td>$p_T^{miss}$ [GeV]</td>
<td></td>
<td>$&gt; 30$</td>
</tr>
<tr>
<td>$\Delta\phi(E_T^{miss}, p_T^{miss})$</td>
<td></td>
<td>$&lt; \pi/2$</td>
</tr>
<tr>
<td>$\Delta\phi(E_T^{miss}, h)$</td>
<td></td>
<td>$&gt; 2\pi/3$</td>
</tr>
<tr>
<td>min[$\Delta\phi(E_T^{miss}, \text{small-} R \text{ jet})$]</td>
<td></td>
<td>$&gt; \pi/9$ (2 or 3 jets), $&gt; \pi/6$ (4 $R$ jets)</td>
</tr>
<tr>
<td>$N_{\text{had}}$</td>
<td></td>
<td>$0^{**}$</td>
</tr>
<tr>
<td><strong>1-lepton selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>leading lepton $p_T$ [GeV]</td>
<td>$&gt; 27$</td>
<td>$&gt; 27$</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>$&gt; 40(80^{(4)})$</td>
<td>$&gt; 100$</td>
</tr>
<tr>
<td>$p_T^{T}$ [GeV]</td>
<td>$&gt; \max[150, 710 - 3.3 \cdot 10^5 \text{ GeV}/m_{W}]$</td>
<td>$&gt; \max[150, 394 \cdot \ln(m_{W}/1 \text{ GeV}) - 2350]$</td>
</tr>
<tr>
<td>$m_T(W)$ [GeV]</td>
<td></td>
<td>$\leq 300$</td>
</tr>
<tr>
<td><strong>2-lepton selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>leading lepton $p_T$ [GeV]</td>
<td>$&gt; 27$</td>
<td>$&gt; 27$</td>
</tr>
<tr>
<td>sub-leading lepton $p_T$ [GeV]</td>
<td>$&gt; 7$</td>
<td>$&gt; 25$</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$ [GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 1.15 + 8 \cdot 10^{-3} \cdot m_{W}/1 \text{ GeV}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt; 20 + 9 \cdot \sqrt{m_{W}/1 \text{ GeV}} - 320^{(44)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{T,\ell\ell}$ [GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[87 - 0.030 \cdot m_{W}/1 \text{ GeV}, 97 + 0.013 \cdot m_{W}/1 \text{ GeV}]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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ATLAS-CONF-2017-055

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