ATLAS Searches for Diboson Resonances

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Outline and motivations

The most compelling argument of New Physics at TeV scale is the extreme fine tuning of quantum corrections involving $t$, $\gamma$, $W$, $Z$ and $H$ in order to keep the observed Higgs mass close to the electroweak scale.

$$\frac{M_H^2}{(125 \text{ GeV})^2} = - \frac{3}{8\pi^2} \lambda_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 - 2\mu^2$$

Tuning for $\Lambda_{\text{cut-off}} = 10 \text{ TeV}$

Fine tuning $< 10\%$ $\Rightarrow$ $\Lambda_{\text{NP}} \sim 1 \text{ TeV}$

New resonances coupled to $\gamma/W/Z/H$ generally expected at multi-TeV scale. The Higgs itself could be the first of a series of di-boson resonances waiting discovery at LHC.
Benchmark models

Three models differing from new boson(s) spin:

Spin 0: Extended Higgs sector (2HDM, ew-singlet model ....... SUSY, ...)
  - Heavy scalars H’

Spin 1: Heavy Vector Triplets (HVT) → W’-W’+Z’
  - Additional SU(2) symmetry
  - Small set of parameters:
    - Mass M_{V’}
    - Coupling to Bosons and Higgs g_V (enable VV, VH, HH decays)
    - Universal coupling to fermions g_F = g^2_{EW}/g_F
  - Model A: equal BRs to fermions and bosons (g_V=1) → Extended Gauge Symm.
  - Model B: couplings to fermions suppressed (g_V=3) → Minimal Composite Higgs

Spin 2: KK graviton from bulk Randall-Sundrum model → G*
  - KK graviton in 5D warped ADS space with SM particles on 1 TeV brane extending into the “bulk”.
  - Couplings to light fermions and VBF production suppressed
Categorization in production mechanisms increases sensitivity

- **Drell-Yan**
  - Heavy Vector Triplet $W'$

- **gluon-gluon fusion**
  - Heavy scalar - RS bulk $G^*$

- **Vector Boson Fusion**
  - Heavy scalar/vector

**VBF**

Two opposite hemisphere jets, $j_1$ and $j_2$, with large rapidity separation and large invariant mass

Ex. $VV \rightarrow llqq$:

- $\eta_{j_1} \cdot \eta_{j_2} < 0$
- $|\Delta \eta_{j_1j_2}| > 4.7$
- $m_{j_1j_2} > 770$ GeV
Current status of VV searches in ATLAS

<table>
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<tr>
<th></th>
<th>W→</th>
<th>Z→</th>
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<tbody>
<tr>
<td>w</td>
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Combination increases sensitivity

THIS TALK: hadronic and semileptonic

- qqqq ~ 45%
- qql(v)v ~ 15%
- qql, lv lv lvv ~ 5%
- llvv ~ 1%
- llll ~ 0.5%

See P.J.Falke and V. Pascuzzi

Not treated here: Search for X→γ+W/Z/H→γ+fat jet (arxiv:1805.01908) NEW

See plenary X.C.Vidal

"Exotic searches - prompt signatures"
Analysis strategy

1. Search for a resonant structure into invariant mass or broad enhancement into transverse mass.
2. Background estimation: full data-driven or/and MC based.

Best performance at high masses where BG is smaller.
Jet trimming and boosted objects

Trimming removes soft QCD and pile-up and leave collinear radiation in jets.

2 resolved jets $R=0.4$
1 large-jets $R=1$

$W/Z/H$

Boosted jet $p_T$

$M_X > 200 \text{GeV}$

$D_2^{(\beta)} = \sum_{i < j < k \in J} p_{T_i} p_{T_j} p_{T_k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^\beta$

- A. Boosted $W/Z$ tagging with $D_2^{\beta=1}$
- B. Boosted $H$ tagging with sub-jets b-tag

+ $M_J$
V and H tagging performance

ATLAS search of $X \rightarrow VV \rightarrow JJ$

@ 13 TeV 79.8 fb$^{-1}$

**ATLAS Simulation Preliminary**

$\sqrt{s} = 13$ TeV

anti $k_{T}$ $R=1.0$, WZ $\rightarrow$ $qqqq$

$|\eta^{jet}|<2.0$, $p_{T}^{jet}>200$ GeV

D$^{2}$ resolution for topo-cluster jets and jets built using combined and neutral Track CaloClusters.

VH signal acceptance $\times$ efficiency including trigger, reconstruction and selection

ATLAS search of

$X \rightarrow VH \rightarrow qqbb/qqcc$

arXiv:1707.06958
VV fully hadronic: VV → JJ

Selection:
- Highest BR ~ 50%
- Merged regime only: 2 large-R jets
- 5 non exclusive SR: WW, ZZ, WZ, WW+WZ, WW+ZZ

BG evaluation fully data-driven:
- Multi-jets QCD (~85%), diboson, V+j, ttbar.
- Binned ML fit to m_{JJ} spectrum assuming a smoothly falling distribution
- 3 VR inverting |Δy_{JJ}| cut and V-tag of WZ SR

$$\frac{dn}{dx} = p_1(1 - x)^{p_2 - \xi}x^{-p_3}$$
**VH fully hadronic: VH→JJ**

**Selection:**
- 2 large-R jets
- Higher mass jet is the H candidate and the other is W/Z tagged.
- WH/ZH overlap by ∼60%.
- Signal regions with 1-2 b-tags.

**BG estimation:**
- Multi-jets QCD >90%.
- Data-driven estimation:
  - functional form from CR with 0-tags.
  - normalization and corrections from high SB mass of the Higgs.
**HH fully hadronic: HH→bbbb, HH→JJ**

**Boosted selection:**
- 36.1 fb-1 from fat-jet trigger
- Categorise into 2,3,4 b-tagged track-jets

**Resolved selection:**
- 27.5 fb-1 from b-jet trigger
- Pair highest score b-jets based on ΔR_{jj} and Δm_{2j}

**BG evaluation:**
- Multi-jets QCD shape from lower b-tag data and ttbar shape from MC.
- Correct iteratively multi-jets QCD kinematics to higher b-tag data by reweights derived from SB data
- BG’s normalisation from simultaneous fit to 3 BG enriched regions and Higgs SB
HH fully hadronic: $HH \rightarrow b\bar{b}b\bar{b}$, $HH \rightarrow JJ$

**Results:**
- Simultaneous fit to resolved and boosted discriminant $M_{4j}$ and $M_{2J}$
- Limits on mass range: 260–1400 GeV for resolved and 800–3000 GeV for boosted
- Set limits on heavy scalar and spin-2 bulk RS graviton

**ATLAS**
- $\sqrt{s} = 13$ TeV, 27.5-36.1 fb$^{-1}$
- Observed 95% CL limit
- Expected 95% CL limit
- Local dev. 2.5 $\sigma$
- 313 GeV
- Global 2.3 $\sigma$
- $M_{hh} = 280$ GeV

$\sigma(pp \rightarrow G_{kk} \rightarrow b\bar{b}b\bar{b})$ vs $m(G_{kk})$ (TeV)

$\sigma(pp \rightarrow \text{Scalar} \rightarrow b\bar{b}b\bar{b})$ vs $m($Scalar$)$ (TeV)
ZV → llqq, vvqq semi-leptonic

ZV → llqq selection:
7 signal regions to increase sensitivity:
• Merged: one large R jet W/Z tagged (dominant above 800 GeV)
  • splitted in High and Low Purity SR defined by <50% and 50-80% of W/Z tagger Work Point.
• Resolved: two small radius jets with invariant mass compatible to W/Z
• ggF/DY splitted in untag and b-tag

ZV → vvqq selection:
similar to ZV → llqq but:
• Only Merged selection
• VBF looser cut m_{j1j2} > 630 GeV
• No leptons and E_{Tmiss} > 250 GeV
• Topological cuts to suppress multi-jets

BG evaluation data-driven:
• 7 CR for Z+jets (from qq SB)
• 4 CR for W+jets (from qq SB)
• 5 CR for ttbar (from eu selection)
ZV → \(llqq\), \(vvqq\) semi-leptonic

- Dominant BG is Z+jet for both but for \(llvv\) also W+jet and t\(t\)\(\bar{t}\) are significant
- \(V+\)jets and \(t\(t\)\(\bar{t}\)\) normalization from CR, di-boson from MC

VBF xsec smaller than ggF
Sensitivity often larger for VBF than ggF
**WV → bqq semi-leptonic**

**Selection:**
- VBF and ggF/DY categorization
- Merged and Resolved selections
- 1 lepton + $E_T^{miss}$
- $E_T^{miss}/p_T(l\nu) > 0.2$ suppress Multi-jets QCD Background

**BG evaluation:**
- 50-70% W+jets, 20-30% ttbar
- 5% Z+jets+di-boson+single t
- Multi-jets <1% for Merged and 5% for Resolved
**Selection:**

- Resolved and Merged selections for $H \rightarrow bb$ with priority to resolved for better invariant mass resolution and less BG.
- Signal discriminant:
  - 0-lepton is ZH transverse mass
  - 1-lepton WH mass with two-fold ambiguity
  - 2-leptons ZH invariant mass.
- Many cuts to remove Multi-jets QCD and non-collision BG to $10^{-4}$ negligible level.

**BG evaluation:**

- 0(2)-lepton: Z+jets, tt, W+jets
- 1-lepton: tt, single t, W+jets

<table>
<thead>
<tr>
<th>Fit</th>
<th>Channel</th>
<th>Resolved signal regions</th>
<th>Merged signal regions</th>
<th>Resolved control regions</th>
</tr>
</thead>
</table>
| $A$  | 0-lepton 2-lepton | 1, 2, 3+ b-tag | 1, 2 b-tag, and 1, 2 b-tag add. b-tag | $1+2 b$-tag, $3+ b$-tag $e\mu$
| $Z'$, $W'$ | 0-lepton 1-lepton 2-lepton | 1, 2 b-tag | 1, 2 b-tag | $1+2 b$-tag $m_{jj}$ sideband |

**Definition of SR and CR different for V decay mode and model hypothesis**

- CP-odd scalar boson $A \rightarrow ZHbb$
Combination at 36.1 fb$^{-1}$

**HVT $V' \rightarrow VV + VH$**

- **HVT A**: 4.2 TeV
- **HVT B**: 4.5 TeV

**$G_{KK} \rightarrow WW + ZZ$**

- **2.2 TeV**
Conclusions

- Di-boson resonances searches at TeV scale are strongly motivated by naturalness principle
- Improving reconstruction and advanced analyses techniques we can get the most out of the data:
  - Boosted object tagging
  - New techniques in jet reconstruction and b-tagging
  - Machine learning methods applied to object definition and analysis selection
  - Statistical combinations of different decay modes
- With 2018 data an integrated luminosity of 140 fb$^{-1}$ is expected

A bright future in front of us with full run II, run III and HL-LHC
Event topology

Merged or resolved W/Z/H

0 leptons

VV(H)

Merged or resolved W/Z/H

1 lepton + MET

WV(H)

Merged or resolved W/Z/H

2 leptons

ZV(H)

Merged or resolved W/Z/H

0 lepton + MET

ZV(H)

Merged or resolved W/Z/H
Jet trimming

Jet trimming

Initial jet

Trimmed jet

\( \frac{p_T'}{p_T} < f_{cut} \)

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

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

JHEP 1309 (2013) 076
Jet substructure

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

$$E_{CF1}(β) = \sum_{i \in J} p_{T_i}$$
$$E_{CF2}(β) = \sum_{i < j \in J} p_{T_i} p_{T_j} (ΔR_{ij})^β$$
$$E_{CF3}(β) = \sum_{i < j < k \in J} p_{T_i} p_{T_j} p_{T_k} (ΔR_{ij} ΔR_{ik} ΔR_{jk})^β$$

$$D_2^{β=1} = E_{CF3} \left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

ATLAS Simulation

$\sqrt{s} = 8$ TeV

$H_T^{Truth} < 1.2$

$500 < p_T^{Truth} < 1000$ GeV

M Cut

anti-$k_T$, $R=1.0$ jets

Trimmed ($f_{cut} = 5\%, R_{sub} = 0.2$)

EPJC 76(3), 1-47
Combined jet mass

- The jet mass resolution is further improved by combining calorimeter and tracking information:

\[ m_J = w_{\text{calo}} \times m_j^{\text{calo}} + w_{\text{track}} \times \left( m_j^{\text{track}} \frac{p_T^{\text{calo}}}{p_T^{\text{track}}} \right) \]

- \( w_{\text{calo}} \) and \( w_{\text{track}} \) are inversely proportional to the square of the resolution of each mass term and are optimized to minimize the combined jet mass resolution.

- Resolution is improved especially at high jet \( p_T \), due to the coarser angular resolution of the calorimeter.

- For Higgs boson reconstruction in the bb decay channel, the mass resolution can also be improved by correcting for semi-leptonic decays of the b-hadrons.
b-tagging

- Crucial for reconstructing Higgs to $b\bar{b}$-bar decays but also for rejecting top backgrounds.
- A $b$-hadron decay in the detector provides a measurable displaced secondary vertex.
- 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.
VV fully hadronic: VV → JJ

**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \sigma (pp \rightarrow V' \rightarrow WW+WZ) [fb] \]

- Phys. Lett. B 777 (2018) 91 (Scaled to 79.8 fb⁻¹)
- Current Result (79.8 fb⁻¹)
ZV → llqq, vvqq semi-leptonic

**ATLAS**

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

- Data
  - Z + jets
  - Top Quarks
  - W + jets
  - SM Diboson
  - Total Uncertainty

**Events**

- **Data/Postfit**
  - VBF cat. high-purity
  - VBF cat. low-purity
  - ggF cat. high-purity
  - ggF cat. low-purity
  - ggF cat. b-tagged
  - ggF cat. untagged

- **Postfit/Prefit**
  - from qq SideBand
  - from eu selection