ATLAS Searches for $W W / Z \gamma$ Resonances

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On behalf of ATLAS collaboration

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Introduction

- Many BSM theories predict heavy resonances decaying to heavy quarks or bosons
  - Spin-0
    ‣ 2HDM, additional scalar singlets
  - Spin-1
    ‣ Heavy Vector Triplets, Composite Higgs
  - Spin-2
    ‣ Randall-Sundrum (RS) graviton mode

- Di-boson resonance searches highly motivated!

✓ This talk covers \(VV\) and \(V\gamma\) (\(V = W/Z\)) decay modes

NEW results in LHC-ATLAS Run2 with 36.1 fb\(^{-1}\)
High mass object searches with $W$

- Production
  - Gluon-gluon fusion (ggF)
  - Quark-antiquark interaction (qqbar)
  - Vector-boson fusion (VBF)
    - 2 forward jets tagged

- Decay channels of vector boson

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>W (%)</th>
<th>Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\nu/\ell\ell$</td>
<td>10.7% x2</td>
<td>3.3% x2</td>
</tr>
<tr>
<td>$\tau\nu/\tau\tau$</td>
<td>11.4%</td>
<td>3.3%</td>
</tr>
<tr>
<td>$\nu\nu$</td>
<td>-</td>
<td>20.0%</td>
</tr>
<tr>
<td>$qq^{(\ast)}$</td>
<td>67.4%</td>
<td>69.9%</td>
</tr>
</tbody>
</table>

- Leptonic decays
  - Small branching fractions
  - Clean final states
- Hadronic decays
  - Large branching fractions
  - More backgrounds from QCD events
  - **Boson tagging with large-R jets**

- Methodology
  - To search for excesses above backgrounds in the $VV$ invariant mass distribution
Boosted vector boson tagging

- Event categories
  - Resolved
    - Small-R jet (R=0.4) : j
  - Merged (boosted)
    - Large-R jet (R=1.0) : J
      - New techniques developed for boosted-V ID
        - Combinations with jet mass and jet-substructure variables

- Decay channels
  - All hadronic
  - Semi-leptonic
    - 0/1/2 leptons
  - All leptonic
    - $ZZ \rightarrow 4\ell, 2\ell 2\nu$, $WW\rightarrow \ell\nu\ell\nu$

\[ \Delta R \sim \frac{2M}{p_T} \]

$W \rightarrow qq$

ATLAS Simulation
Pythia $Z' \rightarrow tf$, $t \rightarrow Wb$

JHEP09(2013)076
Boosted vector boson tagging

- Trimming of large-R jet
  - Remove constituents with $p_T(\text{const})/p_T(\text{jet}) < 5\%$

- Track-assisted jet-mass
  - $m^{\text{TA}} = m^{\text{track}} \times \frac{p_T^{\text{calo}}}{p_T^{\text{track}}}$

- Substructure variable
  - "D2"

For 2-pronginess

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV, W/Z-jets

1.6 TeV < $p_T$ < 1.8 TeV, $|\eta| < 0.4$

$\eta < 2.0$, W-jets

Fit: fourth order polynomial

ATL-PHYS-PUB-2015-033
The unique kinematic signature of the VBF process is used to define event categories enriched in this process through different mass windows. Analysis, where a high-purity (HP) or low-purity (LP) working point (WP) is defined as a function of the production rate, is used to reconstruct the hadronically decaying boson, requiring no overlap with either of the tag-jets in the VBF category. In case there are more than two tag-jets, the pair with the largest invariant mass is chosen. Events that fail the VBF selection are assigned to the ggF category. The 50% and 80% efficiency working points (HP; LP) are classified as VBF candidates. In case there are more than two tag-jets, the pair with the highest jet mass is chosen. Events that fail the VBF selection are assigned to the ggF category.

Sub-categories in the merged:
- High/Low purity (HP/LP) regions
  - 50/80% working point with D2
- Large-R jet mass

Backgrounds:
- W+jets (main), t
t
t
tab, SM diboson, Z+jets, QCD (resolved)

Systematic uncertainties:
- Jet energy/mass scale
- jet-substructure
**ZZ/ZW → ℓ ℓ qq / ν ν qq searches**

- **Models**
  - Spin-0/1/2 interpretations tested
- **Production**
  - VBF: requiring additional 2 small-R jet with respect to ggF
- **Event categories**
  - Resolved : V → 2 small-R jets
    (used only for ℓ ℓ qq)
  - Merged : V → 1 large-R jet

- **Backgrounds**
  - Z+jets, W+jets, ttbar, SM WW
- **Systematic uncertainties**
  - Jet energy scale, jet mass scale, jet-substructure,
  - ℓ ℓ qq : Z+jets modeling,
  ν ν qq : W+jets modeling

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**Figure 8:** Comparisons of the observed data and expected background distributions of the final discriminants of the ggF category for the H → ZZ → ℓℓqq search: (a) high-purity and (b) low-purity signal regions. For illustration, expected distributions from the ggF production of a 1 TeV Higgs boson with \( \mathcal{B}(H → ZZ → ℓℓqq) = 20 \) fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.

**Figure 9:** Comparisons of the observed data and expected background distributions of \( m_T \) in the VBF category of the H → ZZ → ℓℓqq search: (a) high-purity and (b) low-purity signal regions. For illustration, expected distributions from the VBF production of a 1.6 TeV Higgs boson with \( \mathcal{B}(H → ZZ → ℓℓqq) = 6 \) fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
**VW → qqqq search**

- **Event selection**
  - 2 large-R jets
  - Missing $E_T < 250$ GeV
- **Background estimation**
  - Multi-jet QCD events dominate
    - High purity signal regions only
- **Modeling**
  
  $$\frac{d\eta}{dx} = p_1 (1 - x)^{(p_2 - \xi p_3)} x^{-p_3}$$

  - $x = m_\eta/\sqrt{s}$
  - $p_1$: normalization, $p_2$, $p_3$: shape parameters
  - $\xi$: to remove the correlation between $p_2$ and $p_3$ in the fitting

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**ATLAS**

$\sqrt{s} = 13$ TeV, 36.7 fb$^{-1}$

**WW+WZ**

- Data
- Fit
- Fit + HVT model B $m=1.5$ TeV
- Fit + HVT model B $m=2.4$ TeV

**WW+ZZ**

- Data
- Fit
- Fit + Bulk RS $m=1.5$ TeV ($\times$ 10)
- Fit + Bulk RS $m=2.4$ TeV ($\times$ 10)

$\chi^2$/DOF = 7.2/9

$\chi^2$/DOF = 4.1/8

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**arXiv:1708.04445**
Summary: Hadronic $W' \rightarrow WZ$ searches

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

95% C.L. exclusion limits

- **HVT model B $g_v = 3$**
- **Observed**
- **Expected**
- $qqqq$
- $l\nu qq$
- $llqq$
- $vvqq$
- $\nu\nu qq$

- $l l qq \leftrightarrow \nu \nu qq$
  - low mass region
    - Good / bad mass resolution
  - high mass region
    - Statistically limited / high statistics
- $l\nu qq$
  - Good sensitivity in wide mass region
- $qqqq$
  - Low mass region
    - QCD background
  - High mass region
    - JES uncertainty
WW → eνμν search

- Event selections
  - single lepton triggers
  - leptons
    - tight identification, isolation
    - opposite sign electron and muon pair
  - Number of jets
    - ggF: 0 jets
    - VBF: 1 or 2 jets
- Backgrounds
  - SM WW (main for ggF), ttbar (main for VBF)

Figure 4: Post-fit distributions of the transverse mass $m_T$ in the SR ggF (top left), SR VBF1J (top right) and SR VBF2J (bottom) categories. In each plot, the last bin contains the overflow. The hatched band in the upper and lower panels shows the total uncertainty of the fit. The top-quark and WW background event yields are scaled using the indicated normalisation factors obtained from the simultaneous fit to all signal and control regions. The heavy Higgs boson signal event yield is normalised to the expected limits on $H \rightarrow WW$ and is shown for masses of 700 GeV and 2 TeV in the NWA scenario.
• Result
- No excess in spin-0/2 analyses

\[
\sigma_r \times B(H \rightarrow WW) \text{ [pb]}
\]

\[
\sigma_r \times B(H \rightarrow WW) \text{ [pb]}
\]

\[
\sigma_r \times B(X \rightarrow WW) \text{ [pb]}
\]

\[
\sigma_r \times B(X \rightarrow WW) \text{ [pb]}
\]
**ZZ → 4ℓ**

- **Signal selections**
  - single lepton triggers
  - leptons
    - tight identification, isolation
    - opposite sign leptons for 4ℓ, 2e2μ
  - Z-mass window

- **Backgrounds**
  - SM ZZ(main), ttbar+V, VVV, Z+jets

**ZZ → ℓ ℓ ℓ ν ν**

- **Signal selections**
  - single lepton triggers
  - leptons
    - tight identification, isolation
    - N=2, opposite sign,
  - Z-mass window
  - Missing $E_T > 120$ GeV

- **Backgrounds**
  - SM ZZ(main), WZ, Z+jets
**Results**
- No significant excess observed
- Limits set for 2HDM Type I / II
High mass $Z\gamma$ resonance search

- Performed in parallel with the SM Higgs decay
  \[ H(X) \rightarrow Z\gamma \rightarrow \ell\ell\gamma \]
- Event selection
  - Triggers
    - Single / di-lepton triggers
  - Photons
    - Tight identification
  - Leptons (ee or $\mu\mu$)
    - Tight identification and isolation
  - $Z$ boson
    - 2 leptons
    - Mass window: $91.2 \pm 15$ GeV

- Signal modeling
  - narrow spin-0/2 resonance
- Backgrounds
  - SM $Z + \gamma$, $Z +$ jet events with fitting

**Figure 6**

- Background fit

<table>
<thead>
<tr>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
</tr>
<tr>
<td>$e^-/\mu^-$</td>
</tr>
<tr>
<td>$H$ or $X$</td>
</tr>
</tbody>
</table>

**Results**

- Observed
  - $\ell\ell\gamma$ events:
    - Low: 1.8 fb, 2.4 fb, 1.5 fb
    - High: 88 fb, 117 fb, 94 fb
- Expected (SM) prediction: 1.0 (0.5)

**Performance**

- $\pm 25\%$ yield
- Largest deviation: local (global) significance of 2.5 (2.7) at 125.09 GeV

**Event Categorization**

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data ($Z + \gamma$ events)</td>
<td>3-25, 2000-4000 GeV</td>
</tr>
<tr>
<td>$Z +$ jet background</td>
<td>1000-1400 GeV</td>
</tr>
</tbody>
</table>

**Significance**

- $m_{Z\gamma}$ [GeV]
- Significance
- $\sigma$ [GeV]
- $95\%$ CL Upper Limit on $B [fb]$
• Results
  - Data consistent with Standard Model background-only hypothesis
  - Largest deviation
    ‣ local (global) significance of 2.7(0.8) $\sigma$ at 960 GeV
  - Main uncertainties
    ‣ $e/\gamma$ resolution
      - 4 - 30% on signal width
    ‣ background bias
      - 0 - 6% on signal yield

\[ \text{spin-0, } ggF \]

\[ \text{spin-2, } ggF \]

\[ \text{spin-0, } gq \]

\[ \text{spin-2, } gq \]
Summary

- Di-boson resonance searches in ATLAS
  - High mass state motivated by multiple BSM models
    ‣ Direct way to explore the TeV scale
  - Experimentally challenging
    ‣ Highest energy/momentum measurement
    ‣ Boosted object tagging with large-R jet
  - Results
    ‣ No statistically significant excess observed in ATLAS

✓ Much more data coming in Run2 for more strict limits, or discoveries. Stay tuned!
Backup
Experimental apparatus

The ATLAS detector

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Semiconductor tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
13 TeV / 8 TeV inclusive parton luminosity ratio

**Equation:**
\[
\frac{\partial L_{ab}}{\partial M_X^2} = \frac{1}{s} \int_{\tau}^{1} \frac{dx}{x} f_a(x, M_X^2) f_b(\tau/x, M_X^2), \quad \tau = \frac{M_X^2}{s}
\]

**Graph:**
- **gg**
- **Σqq**
- **qg**

- Strong interaction dominated processes
- Electroweak processes

**Legend:**
- **WJS2013**
- **MSTW2008NLO**
Substructure variable

• Definitions

\[ ECF(N, \beta) = \sum_{i_1 < i_2 < \ldots < i_N \in J} \left( \prod_{a=1}^{N} E_{i_a} \right) \left( \prod_{b=1}^{N-1} \prod_{c=b+1}^{N} \theta_{i_b i_c} \right) \]

\[ D_2^{\beta=1} = ECF(3) \left( \frac{ECF(2)}{ECF(1)} \right)^3 \]
**Results**
- no significant excess
  ‣ qqbar, ggF, VBF productions
  ‣ Scalar, vector triplet, graviton interpretations
**WW/WZ → ℓ ν qq searches**

- **Result**
  - Consistent BG estimate with data
  - HVT Model A
    - Triplet model similar to SSM, dominant couplings to fermions
  - HVT Model B
    - Triplet model similar to composite Higgs, ggF suppressed

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**ATLAS**

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

- **ggF/qq lvqq Category**
  - HVT model Z
  - Expected 95% CL upper limit
  - Observed 95% CL upper limit

- **σ(pp → Z → WW)** [pb]

- **σ(pp → Z → WW)** [pb]

- **σ(pp → W → WZ)** [pb]

- **σ(pp → G → WW)** [pb]

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**ATLAS**

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

- **ggF/qq lvqq Category**
  - HVT model W
  - Expected 95% CL upper limit
  - Observed 95% CL upper limit

- **σ(pp → W → WZ)** [pb]

- **σ(pp → W → WZ)** [pb]

- **σ(pp → G → WW)** [pb]

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**ATLAS**

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

- **ggF/qq lvqq Category**
  - Heavy scalar model
  - Expected 95% CL upper limit
  - Observed 95% CL upper limit

- **σ(pp → H → WW)** [pb]

- **σ(pp → H → WW)** [pb]

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**ATLAS**

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

- **ggF/qq lvqq Category**
  - Bulk RS model k/M_* = 1.0
  - Expected 95% CL upper limit
  - Observed 95% CL upper limit

- **σ(pp → G → WW)** [pb]

- **σ(pp → G → WW)** [pb]
**VV → qqqq search**

- **Results**
  - No significant excess observed
  - Interpretations: scalar, vector triplets, bulk gravitons

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![Graphs showing results for VV → qqqq search](image-url)
References

- "Search for diboson resonances with boson-tagged jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"
    › submitted to PLB

- "Searches for heavy ZZ and ZW resonances in the $\ell \ell qq$ and $\nu \nu qq$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"
    › submitted to JHEP

- "Search for WW/WZ resonance production in $\ell \nu qq$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"
    › submitted to JHEP

- "Search for heavy resonances decaying into WW in the $e \nu \mu \nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"
    › submitted to EPJC

- "Search for heavy ZZ resonances in the $\ell^+ \ell^- \ell^+ \ell^-$ and $\ell^+ \ell^- \nu \nu$ final states using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"
  - [http://cds.cern.ch/record/2273874](http://cds.cern.ch/record/2273874)
    › ATLAS-CONF-2017-0589

- "Searches for the $Z\gamma$ decay mode of the Higgs boson and for new high-mass resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"