ATLAS Searches for VV and Vγ Resonances

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On behalf of the ATLAS Collaboration

Phenomenology 2017 Symposium
8-10 May 2017
How to find new physics - the easy way!

**General idea**
- Search for new particle $Z \rightarrow XX$ or $XY$
- Reconstruct invariant mass $m_{XX/XY}$
- Search for narrow resonance on top of background

**Analyses presented today based on 13.2 - 15.5 fb$^{-1}$ taken in 2015+2016**

1. $WZ/ZZ \rightarrow llqq$ ATLAS-CONF-2016-082
2. $WZ/ZZ \rightarrow \nu\nu qq$ ATLAS-CONF-2016-082
3. $WW/WZ \rightarrow l\nu qq$ ATLAS-CONF-2016-062
4. $WW/WZ/ZZ \rightarrow qqqq$ ATLAS-CONF-2016-055
5. $Z\gamma \rightarrow ll\gamma$ ATLAS-CONF-2016-044

*See Mark Oreglia’s talk on VH and HH resonances
**Diboson resonance searches with hadronic decays rely on substructure techniques

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Benchmark models for $VV$ and $V\gamma$ resonances

1. Bulk Randall-Sundrum model
   - Model of warped extra dimensions
   - Spin-2 Kaluza-Klein graviton ($G^*$)
   - $G^* \rightarrow WW, ZZ$
   - $\text{BR}(G^* \rightarrow WW/ZZ) \approx 20/10\%$

2. Heavy Vector Triplet
   - Simplified phenomenological Lagrangian
   - Spin-1 gauge bosons ($W'$, $Z'$)
   - $W' \rightarrow WZ$ and $Z' \rightarrow WW$
   - $\text{BR}(W' \rightarrow WZ) \approx 2\%$

3. Heavy Higgs
   - Spin-0 H boson, narrow width approx.
   - $H \rightarrow WW/ZZ$
   - *Naive dimensional analysis* and *unsuppressed* gluon coupling

4. Scalar boson $X$
   - gg fusion production
   - $X \rightarrow Z + \gamma$
   - Intrinsic decay width of 4 MeV to $Z + \gamma$
Boosted boson tagging in Run-II searches in ATLAS

1. **Jet algorithm**: anti-$k_t$ jets with radius parameter $R = 1.0$

2. **Grooming algorithm**: trimming with $R_{\text{sub}} = 0.2$ and $f_{\text{cut}} = 5\%$ (subjets are re-clustered with $k_t$ algorithm)

3. **Boson tagging**: 50% flat signal efficiency ($\sim 2\%$ QCD eff.)
   - large-radius jet mass ($\pm 15$ GeV window around boson mass)
   - Energy correlation variable $D_2^{\beta=1}$

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**Graphs:**

- **Signal & W+jets Regions (HP):**
  - M$_{\text{leading}}$ vs. Events / 10 GeV
  - Data / MC
  - ATLAS Preliminary

- **Events / 0.2 GeV:**
  - Data (2015+2016)
  - W+jets
  - Top
  - Single-t
  - Dibosons
  - Z+jets
  - SM total
  - ATLAS Preliminary

- **Signal Regions (HP & LP):**
  - $D_2^{\beta=1}$

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\[ ZV \rightarrow \ell\ell qq \]

**Event selection**

- 2 isolated same flavour leptons, \( m_{\ell\ell} \) compatible with \( Z \) boson mass
- Merged (one large-R jet) and resolved (two \( R = 0.4 \) jets) analyses
- High and low purity signal regions based on \( D_2 \)
- \( \sqrt{p_T^2(\ell\ell) + p_T^2(jj)} / m_{\ell\ell jj} > 0.4(0.5) \) for \( H (W', G^*) \)

**Background estimation**

- Shape estimated from MC
- \( Z+\)jets and \( t\bar{t} \) normalisation estimated in CR
- \( t\bar{t} \) CR: diff. flavour leptons, 2 \( b \)-tagged jets
- \( Z+\)jets CR: invert \( Z \) boson mass window

**Dominating systematic uncertainties**

- Jet energy & \( D_2 \) scale and resolution unc.
- \( Z+\)jets modelling
ZV → ℓℓqq - Results

- Observable: invariant mass of decay products $m_{ℓℓjj}$, $m_{ℓℓJ}$
- No significant deviations from SM prediction: 95% CL upper limits on $σ × BR$
- Exclude RS Graviton with masses below 1035 GeV ($\sim 200$ GeV improvement with respect to 2015 analysis based on 3.2 fb$^{-1}$)
- Exclude $W'$ with $m_{W'} < 2225$ GeV ($\sim 800$ GeV improvement)
$ZV \rightarrow \nu\nuqq$

**Event selection**

- Veto leptons, $E_{T}^{\text{miss}} > 250$ GeV
- Multijet and non-collision bkg suppression
  - $p_{T}^{\text{miss}} > 50$ GeV, $\Delta \Phi(\vec{p}_{T}^{\text{miss}}, \vec{E}_{T}^{\text{miss}}) < 1$
  - $\min[\Delta \Phi(\vec{E}_{T}^{\text{miss}}, \text{small} - R \text{ jet})] > 0.4$
- Only merged analysis
- High and low purity signal regions based on $D$

**Background estimation**

- Normalisation of $Z+$jets, $W+$jets and $t\bar{t}$ in signal region determined in control regions
- $Z+$jets CR: $Z \rightarrow \mu\mu + J$ with new $E_{T}^{\text{miss}}$ definition (muon contribution removed)
**ZV → ννqq - Results**

- Simultaneous fit to two signal regions and six control regions
- No significant deviations observed from SM prediction

→ 95% CL upper limits on $\sigma \times \text{BR}$

ATLAS Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Events / GeV</th>
<th>ATLAS</th>
<th>Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 13 \text{ TeV}$, $13.2 \text{ fb}^{-1}$</td>
<td>0 lep. high-purity SR</td>
<td></td>
</tr>
</tbody>
</table>
**Event selection**

- Only merged analysis
- One lepton and $E_{\text{miss}}^T > 200$ GeV
- $\geq 1$ large-$R$ jet
- $p_T(J)/m_{\ell\nu J} > 0.4$, $p_T(\ell\nu)/m_{\ell\nu J} > 0.4$
- Reject events with close-by small-$R$ $b$-tagged jet

**Background estimation**

- Shape estimated from MC
- $W+$jets & $t\bar{t}$ normalisation estimated in CR
- $t\bar{t}$ CR: require close-by $b$-tagged jet

**Dominating systematic uncertainties**

- Energy, mass and $D_2$ scale and resolution uncertainties
- Modelling of background shape
- $\sim 10$-20% effect on signal strength
WV → ℓνqq - Results

- No significant deviations observed from SM prediction
- → 95% CL upper limits on $\sigma \times BR$
- $\sim 1 \ (0.2)$ TeV improvement in mass exclusion limits for HVT (Graviton) with respect to $3.2 \ fb^{-1}$ analysis
Event selection

- Require two large-\( R \) boson-tagged jets
- Additional criteria on number of tracks ghost-associated to ungroomed jet: \( n_{\text{trk}} \)
- Efficiency of \( n_{\text{trk}} \) measured in \( V + \text{jets} \) data
- Overlap between \( WW, WZ, ZZ \) selection

- Dominating background: QCD dijets
- Background parameterised by:

\[
\frac{dn}{dx} = p_1 (1 - x)^{p_2 + \xi p_3} x^{p_3}, \quad x = m_{jj}/\sqrt{s}
\]

- \( p_1 \): normalisation, \( p_2, p_3 \) dimensionless shape parameters, \( \xi \) constant

Binned maximum-likelihood fit performed to data to estimate bkg
No significant deviations from SM prediction observed
→ 95% CL upper limits on $\sigma \times \text{BR}$
- For $g_V = 1\ (3)$, exclude
  - $1.2 < m_{Z'} < 1.8\ (1.9)\ \text{TeV}$
  - $1.2 < m_{W'} < 1.9\ (3.0)\ \text{TeV}$
- No sensitivity to exclude gravitons with studied parameters
**Event selection**

- **Z-boson candidate:**
  - 2 opposite-sign, same-flavour leptons within ± 15 GeV of Z-boson mass
- Choose photon with highest $p_T$
- $X$ mass resolution improvement by kinematic Z-boson mass constraint fit
- Two categories based on lepton flavour

**Signal and background modelling:**

- **Signal:** double-sided Crystal Ball function
- **Bkg:** non-resonant production of a prompt photon & Z boson, $Z+$jets (smoothly falling background)
- **Bkg parameterised with:**

\[
\frac{dn}{dx} = \mathcal{N}(1 - x^k)^p_1 x^p_2, \quad x = m_{Z\gamma}/\sqrt{s}
\]
Selected 306 (485) candidates for $Z \to e^+e^-/\mu^+\mu^-$

No significant deviations from bkg prediction

→ 95% CL upper limits on $\sigma \times \text{BR}$

Results dominated by stat. uncert.
Summary

- The diboson and $Z + \gamma$ final state provides a direct key to new physics beyond the Standard Model.

- The diboson resonance searches rely on using jet substructure techniques to reconstruct boosted hadronically decaying $W/Z$ bosons (challenging when going to higher transverse momenta).

- No significant deviation from background expectation observed at 13 TeV → set upper limits on cross-section $\times$ BR for benchmark models.

- The increased luminosity allowed to improve the exclusion limits of the benchmark models significantly with respect to previous analyses.

- Analyses using the full 2015+2016 dataset will allow to extend the mass reach of these searches even further.
Backup
Challenges of final states with hadronic decays

1. How do we handle the high transverse momentum?

Low $p_T$ vector bosons
- Decay products well separated
- Two small-$R$ jets ($R \approx 0.4$)

High $p_T$ vector bosons
- Decay products are collimated
- One large-$R$ jet ($R \approx 1.0$)
Challenges of final states with hadronic decays

1. How do we handle the high transverse momentum?
2. How can we handle the high pile-up?
   - Jet mass depends on pile-up and mass resolution diminishes with $\langle \mu \rangle$
   - Grooming techniques remove soft gluon radiation and pile-up effects
   - **Trimming**: remove subjets of size $R_{\text{subjet}}$ if $p_T^{\text{subjet}} < f_{\text{cut}} \times p_T^{\text{large-}R}$

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**ATLAS Simulation Preliminary**

anti-\k_{t}, R=1.0 jets

No jet grooming, no jet pileup correction

$|\eta| < 2.0$, $750 < p_T < 1000$ GeV

$\sqrt{s} = 14$ TeV, $Z' \rightarrow t\bar{t}$

\begin{align*}
\langle \mu \rangle &= 80 \\
\langle \mu \rangle &= 140 \\
\langle \mu \rangle &= 200
\end{align*}

---

**Trimmed, no jet pileup correction**

$|\eta| < 2.0$, $750 < p_T < 1000$ GeV

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Challenges of final states with hadronic decays

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2. How can we handle the high pile-up?
   - Jet mass depends on pile-up and mass resolution diminishes with $\langle \mu \rangle$
   - Grooming techniques remove soft gluon radiation and pile-up effects
   - **Trimming**: remove subjets of size $R_{\text{subj}}$ if $p_{T,\text{subj}} < f_{\text{cut}} \times p_{T,\text{large}-R}$
3. How can we suppress the enormous QCD dijet background?
   - $\sigma_{\text{dijet}} \gg \sigma_{\text{BSM}}$ → use **internal structure** of large-$R$ jet

**Quark/gluon jet**

- **One** region with high energy density
- Mass from wide-angle radiation

**W/Z jet**

- **Two** regions with high energy density
- $m_{\text{jet}} \approx m_{W/Z}$
- Balanced subjet $p_T$
Energy correlation variables

Energy correlation $D_2$

\[ D_2^\beta = \frac{E_{CF1}(\beta)}{E_{CF2}(\beta)} \times E_{CF3}(\beta) \]

N-point energy correlation function

\[ E_{CF1}(\beta) = \sum_{i \in J} p_{Ti}, \quad E_{CF2}(\beta) = \sum_{i<j \in J} p_{Ti} p_{Tj} (\Delta R_{ij})^\beta, \]

\[ E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{Ti} p_{Tj} p_{Tk} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^\beta, \]
**Z+jets CR for resolved $H \rightarrow ZZ$ analysis**

- **Z+jets control region for resolved analysis** (same event selection apart from $Z$-boson mass constraint):
  - $50 < m_{jj} < 62$ GeV or $105 < m_{jj} < 150$ GeV
- Resolved analysis is divided in two categories: two $b$-tagged jets (tagged) and events with fewer than two $b$-tagged jets (untagged)
Z+jets CR for merged $H \rightarrow ZZ$ analysis

- Z+jets control region for resolved analysis (same event selection apart from Z-boson mass constraint):
  - $m_J < 65$ GeV or $m_J > 106$ GeV
- Merged analysis divided in two categories: events where jet passed/failed the $D_2$ criteria
Comparison of predicted and observed number of events in MC and data for the merged and resolved $\ell\ell qq$ analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Merged analysis</th>
<th>Resolved analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high purity</td>
<td>low purity</td>
</tr>
<tr>
<td><strong>Signal regions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$576 \pm 22$</td>
<td>$1230 \pm 33$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$49 \pm 7$</td>
<td>$51 \pm 5$</td>
</tr>
<tr>
<td>Top quark</td>
<td>$4 \pm 1$</td>
<td>$5.9 \pm 1.0$</td>
</tr>
<tr>
<td>Total background</td>
<td>$629 \pm 22$</td>
<td>$1287 \pm 34$</td>
</tr>
<tr>
<td>Data</td>
<td>$606$</td>
<td>$1270$</td>
</tr>
<tr>
<td>$H$ (400 GeV)</td>
<td>$1.6 \pm 0.2$</td>
<td>$4.3 \pm 0.7$</td>
</tr>
<tr>
<td>$H$ (700 GeV)</td>
<td>$168 \pm 4$</td>
<td>$88.2 \pm 2.9$</td>
</tr>
<tr>
<td>$H$ (1600 GeV)</td>
<td>$35.9 \pm 0.8$</td>
<td>$24.0 \pm 0.6$</td>
</tr>
</tbody>
</table>
Resolved $H \rightarrow ZZ$ signal region

- Resolved analysis is divided in two categories: two $b$-tagged jets (tagged) and events with fewer than two $b$-tagged jets (untagged)

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

$H \rightarrow ZZ \rightarrow \ell\ell qq$

Tagged SR, ggF

- Data
- H 700 GeV (0.1 pb)
- Z + jets
- Top Quarks
- SM Diboson
- Pre-fit background

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

$H \rightarrow ZZ \rightarrow \ell\ell qq$

Untagged SR, ggF

- Data
- H 700 GeV (0.1 pb)
- Z + jets
- Top Quarks
- SM Diboson
- Pre-fit background
Merged analysis divided in two categories: events where jet passed/failed the $D_2$ criteria
Statistical interpretation of $H \rightarrow ZZ$ analysis

- 95% upper cross-section limits on the $\sigma \times \text{BR}$ of $H \rightarrow ZZ$
- Left: gluon-gluon fusion, Right: VBF
- $\sigma \times \text{BR}$ exclusion limits range from 1.28 (0.6) pb at 300 GeV to 6.2 (5.2) fb at 3000 GeV for ggF and VBF
Statistical interpretation of search for $W'$ and $G^*$

- 95% upper cross-section limits on the $\sigma \times \text{BR}$ of $H \rightarrow ZZ$
- $\sigma \times \text{BR}$ exclusion limits range from
  - 1.10 pb at 500 GeV to 13.9 fb at 5000 GeV for HVT
  - 730 fb at 500 GeV to 6.7 fb at 5000 GeV for RS graviton
- Observed (expected) limits exclude $m_{W'} < 2225$ (2075) GeV and $m_{G^*} < 1035$ (1045) GeV
Z+jets CR for Z\nu\mu \rightarrow \nu\nu qq analysis

- Z \rightarrow \mu\mu + jets events
- Large-R jet required to be outside of Z-mass window (m_J < 65 or m_J > 106 GeV)
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria
- Modified definition of E_T^{miss} used (without muon contribution)
Top control region for $ZV \rightarrow \nu\nu qq$ analysis

- Exactly one muon candidate and at least one large-$R$ jet
- At least one $b$-tagged jet is required
- Large-$R$ jet required to be consistent with $W$ boson decay
- Merged analysis divided in two categories: events where jet passed/failed the $D_2$ criteria
$W+\text{jets CR for } ZV \rightarrow \nu\nu qq$ analysis

- Exactly one muon candidate and at least one large-$R$ jet
- At least one $b$-tagged jet is required
- Large-$R$ jet required to be outside of $W$ boson mass window
- Merged analysis divided in two categories: events where jet passed/failed the $D_2$ criteria

**Graphs:**

- Left graph: 1 lep. high-purity WCR
- Right graph: 1 lep. low-purity WCR

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ATLAS Searches for VV and Vγ Resonances
**Comparison of predicted and observed number of events in MC and data for the high and low purity signal region of the $\nu\nu qq$ analysis**

<table>
<thead>
<tr>
<th>Process</th>
<th>Merged analysis</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high-purity</td>
<td>low-purity</td>
<td></td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>1251 ± 56</td>
<td>3130 ± 79</td>
<td></td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>881 ± 45</td>
<td>2092 ± 75</td>
<td></td>
</tr>
<tr>
<td>Diboson</td>
<td>202 ± 14</td>
<td>227 ± 10</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} + \text{single top}$</td>
<td>557 ± 85</td>
<td>610 ± 100</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>2891 ± 50</td>
<td>6059 ± 76</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>2859</td>
<td>6044</td>
<td></td>
</tr>
<tr>
<td>$H (1600 \text{ GeV})$</td>
<td>63.7 ± 1.9</td>
<td>46.2 ± 1.4</td>
<td></td>
</tr>
</tbody>
</table>
Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the $D_2$ criteria.
Statistical interpretation of $ZV \rightarrow \nu\nu qq$ analysis

\begin{itemize}
\item $W' \rightarrow WZ$ excluded for $m_{W'} < 2400$ GeV with $g_V = 1$
\item $G^* \rightarrow ZZ$ excluded for $m_{G^*} < 1100$ GeV
\end{itemize}
### Event selection criteria for the signal region and $W$+jets and $t\bar{t}$ control region

<table>
<thead>
<tr>
<th>Selection</th>
<th>SR: HP (LP)</th>
<th>$W$ CR: HP (LP)</th>
<th>$t\bar{t}$ CR: HP (LP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \ell\nu$ selection</td>
<td>Number of signal leptons</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Number of vetoed leptons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Number of vetoed leptons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt; 100 \text{ GeV}$</td>
<td>$&gt; 100 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>$p_T(\ell\nu)$</td>
<td>$&gt; 200 \text{ GeV}$</td>
<td>$&gt; 200 \text{ GeV}$</td>
</tr>
<tr>
<td>$W/Z \rightarrow J$ selection</td>
<td>Number of large-$R$ jets</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td></td>
<td>Passing the $D_2^{(\beta=1)}$ cut</td>
<td>yes (no)</td>
<td>yes (no)</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>m_{W/Z} - m_J</td>
<td>$</td>
</tr>
<tr>
<td>Topology cuts</td>
<td>$p_T(\ell\nu)/m_{WV}$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td></td>
<td>$p_T(J)/m_{WV}$</td>
<td>$&gt; 0.4$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>Top-quark veto</td>
<td>Number of $b$-tagged jets</td>
<td>0</td>
<td>$\geq 1$</td>
</tr>
</tbody>
</table>
**W+jets CR for **$WV \rightarrow \ell\nu qq$** analysis**

- Mass of large-$R$ jet required to be outside of 15 GeV window around $m_W$
- Zero $b$-tagged jets
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the $D_2$ criteria

![Graphs showing data and MC comparisons for W+jets Control Regions HP and LP](image-url)
**t\bar{t} CR for WV → ℓνqq analysis**

- Large-\(R\) jet required to be compatible with \(W\)-boson decay
- At least one \(b\)-tagged jet
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the \(D_2\) criteria

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**ATLAS Preliminary**

\(\sqrt{s} = 13\) TeV, 13.2/fb

Top Control Region (HP)

- Data 2015-16
- \(W+\text{jets}\)
- \(t\bar{t}\)
- Single-\(t\)
- Dibosons
- \(Z+\text{jets}\)
- Post-fit uncertainty
- HVT \(m = 2.0\) TeV

---

**ATLAS Preliminary**

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Top Control Region (LP)

- Data 2015-16
- \(W+\text{jets}\)
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**ATLAS Searches for VV and Vγ Resonances**

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**WW → ℓνqq signal region**

- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the $D_2$ criteria.

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**ATLAS Preliminary**

\[\sqrt{s} = 13 \text{ TeV}, 13.2/\text{fb}\]

**WW Signal Region (HP)**

- Data 2015-16
- W+jets
- $t\bar{t}$
- Single-$t$
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**WW Signal Region (LP)**

- Data 2015-16
- W+jets
- $t\bar{t}$
- Single-$t$
- Dibosons
- Z+jets
- Post-fit uncertainty
- HVT $m = 2.0 \text{ TeV}$
Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the $D_2$ criteria.
Comparison of predicted and observed number of events in MC and data for the WW signal and control regions $\ell\nu qq$ analysis

<table>
<thead>
<tr>
<th></th>
<th>WW signal region</th>
<th>$W+$jets control region</th>
<th>$t\bar{t}$ control region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-purity category</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W+$jets</td>
<td>1810 ± 63</td>
<td>3182 ± 65</td>
<td>215 ± 12</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>654 ± 50</td>
<td>1020 ± 33</td>
<td>2940 ± 70</td>
</tr>
<tr>
<td>Single-$t$</td>
<td>163 ± 14</td>
<td>200 ± 15</td>
<td>322 ± 23</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>18.0 ± 3.8</td>
<td>53 ± 6</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Diboson</td>
<td>192 ± 31</td>
<td>70 ± 11</td>
<td>19.0 ± 3.8</td>
</tr>
<tr>
<td>Total SM</td>
<td>2830 ± 80</td>
<td>4530 ± 80</td>
<td>3500 ± 80</td>
</tr>
<tr>
<td>Data</td>
<td>2822 ± 53</td>
<td>4534 ± 67</td>
<td>3509 ± 59</td>
</tr>
<tr>
<td><strong>Low-purity category</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W+$jets</td>
<td>5630 ± 94</td>
<td>7320 ± 110</td>
<td>706 ± 37</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>730 ± 50</td>
<td>1410 ± 47</td>
<td>3100 ± 89</td>
</tr>
<tr>
<td>Single-$t$</td>
<td>178 ± 14</td>
<td>290 ± 22</td>
<td>420 ± 31</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>66.6 ± 4.8</td>
<td>134.1 ± 7.7</td>
<td>17.7 ± 2.8</td>
</tr>
<tr>
<td>Dibosons</td>
<td>215 ± 34</td>
<td>150 ± 23</td>
<td>22 ± 4</td>
</tr>
<tr>
<td>Total SM</td>
<td>6820 ± 80</td>
<td>9310 ± 125</td>
<td>4260 ± 120</td>
</tr>
<tr>
<td>Data</td>
<td>6849 ± 83</td>
<td>9276 ± 96</td>
<td>4270 ± 65</td>
</tr>
</tbody>
</table>
Comparison of predicted and observed number of events in MC and data for the WZ signal and control regions $\ell\nu qq$ analysis

<table>
<thead>
<tr>
<th></th>
<th>$WZ$ signal region</th>
<th>$W+$jets control region</th>
<th>$t\bar{t}$ control region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-purity category</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W+$jets</td>
<td>1810 ± 92</td>
<td>3050 ± 120</td>
<td>194 ± 28</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>830 ± 87</td>
<td>1130 ± 82</td>
<td>2300 ± 100</td>
</tr>
<tr>
<td>Single-$t$</td>
<td>160 ± 23</td>
<td>221 ± 26</td>
<td>312 ± 38</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>18.1 ± 5.1</td>
<td>50.7 ± 8.4</td>
<td>11.5 ± 2.6</td>
</tr>
<tr>
<td>Dibosons</td>
<td>165 ± 43</td>
<td>68 ± 18</td>
<td>19.8 ± 5.5</td>
</tr>
<tr>
<td>Total SM</td>
<td>2990 ± 70</td>
<td>4520 ± 97</td>
<td>3510 ± 94</td>
</tr>
<tr>
<td>Data</td>
<td>2972 ± 55</td>
<td>4534 ± 67</td>
<td>3509 ± 59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$W+$jets</th>
<th>$t\bar{t}$</th>
<th>Dibosons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-purity category</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W+$jets</td>
<td>4003 ± 130</td>
<td>7250 ± 196</td>
<td>670 ± 85</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>670 ± 72</td>
<td>1505 ± 120</td>
<td>3150 ± 125</td>
</tr>
<tr>
<td>Single-$t$</td>
<td>153 ± 21</td>
<td>284 ± 33</td>
<td>409 ± 46</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>54.1 ± 4.0</td>
<td>126 ± 12</td>
<td>16.7 ± 3.3</td>
</tr>
<tr>
<td>Dibosons</td>
<td>155 ± 40</td>
<td>135 ± 34</td>
<td>19.2 ± 6.1</td>
</tr>
<tr>
<td>Total SM</td>
<td>5035 ± 100</td>
<td>9300 ± 180</td>
<td>4260 ± 95</td>
</tr>
<tr>
<td>Data</td>
<td>5059 ± 71</td>
<td>9276 ± 96</td>
<td>4270 ± 65</td>
</tr>
</tbody>
</table>
Statistical interpretation of $WV \rightarrow \ell\nu qq$ analysis

- Resonance masses below 2400 GeV are excluded for model-A
- Resonance masses below 2540 GeV are excluded for model-B
- Graviton masses below 1240 GeV are excluded

---

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

- **Observed 95% CL upper limit**
- **Expected 95% CL upper limit**

- **Expected limit ($\pm 1\sigma$)**
- **Expected limit ($\pm 2\sigma$)**

**Observed**

- $\sigma(pp \rightarrow W' \rightarrow WZ)$ HVT Model A, $g_{\gamma}=1$
- $\sigma(pp \rightarrow W' \rightarrow WZ)$ HVT Model B, $g_{\gamma}=3$

---

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

- **Observed 95% CL upper limit**
- **Expected 95% CL upper limit**

- **Expected limit ($\pm 1\sigma$)**
- **Expected limit ($\pm 2\sigma$)**

**Observed**

- $\sigma(pp \rightarrow G^* \rightarrow WW) k / M_{pl} = 1$
Number of ghost-associated tracks $n_{\text{trk}}$

- Study the jet mass distribution in enriched $W/Z+\text{jets}$ events
- $D_2$ criteria applied to select jets and $n_{\text{trk}}$ varied
- Scale factor of 1.06 → 6% systematic uncertainty on $n_{\text{trk}}$
- Improvement of 20-30% of expected sensitivity
Rapidity difference is used to suppress QCD dijet background ($t$-channel production).

- Discriminating power changes with $p_T$
- 10% window around $m_{W'}$ mass
Control regions for $\mathbf{VV \rightarrow JJ}$ search

- Background parameterisation is tested in different control regions
- Large-$R$ jets required to be outside of $W/Z$ boson mass window
Signal regions for $VV \rightarrow JJ$ search

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$

**WW selection**

<table>
<thead>
<tr>
<th>$M_{JJ}$ [TeV]</th>
<th>Events / 0.1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10^4</td>
</tr>
<tr>
<td>1.5</td>
<td>10^3</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>10^0</td>
</tr>
<tr>
<td>3.5</td>
<td>10^{-1}</td>
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</table>

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$

**WZ selection**

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 15.5 fb$^{-1}$

**ZZ selection**

<table>
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</table>

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8-10 May 2017

ATLAS Searches for $VV$ and $V\gamma$ Resonances
Statistical interpretation of $VV \rightarrow JJ$ results

- 95% upper cross-section times Branching ratio limits on the HVT model
- $Z' \rightarrow WW$ excluded for masses 1.2 - 1.8 (1.2-1.9) TeV for HVT model A (B)
- $W' \rightarrow WZ$ excluded for masses 1.2 - 1.9 (1.2 - 3.0) TeV for HVT model A (B)
• Analyses not sensitive enough to RS gravitons with the studied parameters here
Signal efficiency for $Z\gamma$ search

- Signal efficiency as a function of the resonance mass for $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ channel separately

![Graph showing signal efficiency as a function of $m_X$ for $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ channels. The graph includes data points and curves for each channel, with the x-axis labeled as $m_X$ [GeV] and the y-axis labeled as Signal efficiency.]
Data/MC comparison for the $Z\gamma$ signal region

- Data/MC comparison of invariant $Z\gamma$ mass for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channel

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 13.3 \text{ fb}^{-1} \]
$pp \rightarrow X \rightarrow Z\gamma, Z \rightarrow e^+e^-$

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 13.3 \text{ fb}^{-1} \]
$pp \rightarrow X \rightarrow Z\gamma, Z \rightarrow \mu^+\mu^-$

8-10 May 2017

ATLAS Searches for VV and $V\gamma$ Resonances
Invariant $Z\gamma$ mass distributions

- Comparison of invariant $Z\gamma$ mass distribution for two different resonance masses
- Width of $X$ mass distributions degrades significantly in muon channel for higher resonance masses
Background parameterisation for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channel separately