A search for diboson resonances at ATLAS using boson-tagged jets

Using the jet substructure thresher on the QCD haystack

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Resonance searches are the classic methodology to search for new particles and their excitations. In essence, they boil down to, ‘Look for a peak on a smooth background’. Used in searches ranging from quarkonia to the Higgs.
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  - Rediscovering the SM
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- Rediscovering the SM
- New meson states
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In essence they boil down to, ‘Look for a **peak** on a **smooth background**’.

Used in searches ranging from **quarkonia** to the **Higgs**:
- Rediscovering the SM
- New meson states
- New bosons!

\[
\begin{align*}
\text{masses} & \quad \text{weights} \\
\gamma \gamma & \quad \Sigma \\
110 & \quad -5 \\
120 & \quad 0 \\
130 & \quad 5 \\
140 & \quad 10 \\
150 & \quad 15 \\
160 & \quad 20
\end{align*}
\]

\[
\begin{align*}
\text{S/B weighted sum} & \quad \text{Signal strength categories} \\
\text{mass} & \quad \text{weighted sum} \\
\mu & \quad = 125.4 \text{ GeV}
\end{align*}
\]
In searches for exotic models at ATLAS they are used to probe the very highest mass ranges.

An example from Run-1 is the ATLAS dijet resonance search, [arXiv:1407.1376]

- Uses pairs of high $p_T$ anti-kt 0.6 jets
- Searches for narrow mass resonances
- Data driven background model

(Additional nice search using the angular distributions of dijets, [arXiv:1504.00357])
Introduction

- Today I will present a complementary analysis to the dijet, a search for **diboson resonances** using **jet-substructure** performed on the full 8 TeV dataset from ATLAS.
- Which can be found here [arXiv:1506.00962], for those with no patience

- Diboson resonances appear in many extensions to the standard model
- The following analysis concentrates on two **benchmark** models
  - Extended gauge sector models ($W' \rightarrow WZ$)
  - Extra dimensions models ($G_{RS} \rightarrow WW/ZZ$)
- **Low branching ratios** hinder the leptonic searches at the highest masses
- Obviously, a **fully hadronic** search has access to these lost events
- The problem, is controlling the **enormous QCD background** that the leptonic searches were avoiding

<table>
<thead>
<tr>
<th>$W$ $\downarrow$</th>
<th>Diboson branching ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l\nu$ (33%)</td>
<td>23%</td>
</tr>
<tr>
<td>$qq$ (67%)</td>
<td>47%</td>
</tr>
<tr>
<td>$Z \Rightarrow$</td>
<td>qq (70%)</td>
</tr>
</tbody>
</table>

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<th>$W'$ $\rightarrow$</th>
<th>$W$ $\rightarrow$</th>
</tr>
</thead>
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<td>$l\nu$ (33%)</td>
<td>$\nu\nu$ (20%)</td>
</tr>
<tr>
<td>$qq$ (67%)</td>
<td>$l\nu$ (10%)</td>
</tr>
</tbody>
</table>
Vector bosons have mass $\mathcal{O}(0.1 \text{ TeV})$

We are interested in particles of mass $\geq \mathcal{O}(1 \text{ TeV})$

Therefore the decays of the form, $X \rightarrow VV$ with large $m_X$, lead to vector bosons with very high $p_T$

Therefore, boosted decay products become more collimated

Rule of thumb for angular separation of decay products:

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \approx \frac{2m}{p_T}$$
Can roughly separate hadronic boson decays into **two** regimes

**Resolved**
- Lower momentum $W$, $p_T < 160$ GeV
- $W$ decay resolved in **two distinct** anti-kt 0.4 jets

**Boosted**
- Higher momentum $W$, $p_T \gg 160$ GeV
- $W$ decay products can be captured within a single large-$R$ jets ($R \geq 1.0$)

Some overlap in between for **partially** resolved systems

So, how can we use this information to our advantage?
A quick aside: ATLAS calorimetry

- Jets in ATLAS are formed from **topoclusters**
  - Logical combinations of adjacent energy deposits in the calorimeter cells

- The hadronic calorimeters in ATLAS have a **fine** granularity
  - Tile: $\Delta R \approx 0.1$
  - LAr: $\Delta R \approx 0.025$

- We have the resolution to pick apart **large-R** jets and look at the **substructure**

- Therefore we can use the **guts** of boosted jets to our advantage
**Bosonic vs QCD Jets**

**Bosonic jets**
- Form **two** narrow regions with high energy density corresponding to each quark
- Each quark carries a roughly **equal fraction** of the boson momentum in the lab frame
- Jet mass originates from the **boson mass**, i.e. peaked

**QCD jets**
- **Narrow** region with high energy density corresponding to a single quark/gluon
- Majority of the jet momentum is **concentrated** in this single region
- Jet mass originates from the **spread** of the energy deposition by the single parton/any final state radiation, i.e. essentially random
Fat Jet → Grooming → Tagging

1. **Reconstruct decay as fat-jet**
   - Use large-R parameter jet to collect radiation from the original decay

2. **Groom the jet**
   - **Signal**: Remove unwanted jet constituents not from the signal, e.g. pile-up
   - **Background**: Preserve the background characteristics

3. **Tag as boson jet**
   - Use differences between signal and background jet characteristics to reject background jets
Cambridge-Aachen Jets

- **Cambridge-Aachen** jets (CA jets)

- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Calculate the $\Delta R_{ij}$ between all jet constituents
  - Combine **closest constituents** first
  - Merge while $R \leq 1.2$ (in this analysis)
  - If there are no components within 1.2, **redefine as a jet** and remove from the collection of constituents
  - Merge until there are **no components** left

- **NO** $p_T$ dependence!
- Therefore can look into the history and use the $p_T$ splitting information
The BDRS split filtering algorithm, [arXiv:0802.2470], decomposes CA jets sequential clustering to find hard substructure within. Originally defined to find boosted $H \to bb$ decays.

The decomposition follows some simple steps:
- For jet $j$, undo the last step of clustering forming jets $j_1$ and $j_2$ ($m_{j_1} > m_{j_2}$)
- If there was a large mass drop, $m_{j_1} < \mu_{\text{max}} m_j$ and the $p_T$ balance is not too asymmetric, $\frac{\min(p_{Tj_1}^2, p_{Tj_2}^2)}{m_{j_0}^2} \Delta R_{j_1,j_2}^2 \geq y_{\text{min}}$, define $j$ as from a hard splitting and stop
- Otherwise redefine $j$ as $j_1$, discard $j_2$, and continue
- Filter the resulting jet by re-clustering as $n_r \times R_r$ sized subjets
In this analysis a **modified BDRS-A** split filtering algorithm is used.

Starts from $R = 1.2$ CA jets seeded from locally cluster weighted (LCW) topological clusters.

Loose BDRS tagger, with **no mass drop** requirement.

<table>
<thead>
<tr>
<th>Iterative parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{y_{\text{min}}}$</td>
<td>0.20</td>
</tr>
<tr>
<td>$\mu_{\text{max}}$</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Iterative parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_r$</td>
<td>3</td>
</tr>
<tr>
<td>$R_r$</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Particle level jet **energy and mass calibrations** were derived and applied to the BDRS-A CA $R = 1.2$ jets used in the analysis.

Effectively **restores** jet energy/mass response over the **full** jet $E$ and $\eta$ range.

- Calculate the **jet energy response** in bins of $\eta_{\text{det}}$ and $E_{\text{truth}}$.
- Fit the responses with a Gaussian fit, to gain mean response in each bin, $< R_E^{\text{jet}} >$.
- Derive the mean reconstructed jet energy, $< E_{\text{reco}}^{\text{jet}} >$.
- Fit the $< R_E^{\text{jet}} >$ vs $< E_{\text{reco}}^{\text{jet}} >$ distribution to gain a **calibration function**.
- Repeat process for **mass calibration** using the LCW+JES jets.
Killing the Background

- Let me briefly try to quantify the level of the dominant QCD background the analysis will encounter
  - Other backgrounds contribute, at a significantly lower rates
  - All modelled to be smoothly falling
- It is a lot.... an awful lot

<table>
<thead>
<tr>
<th>Leading jet $p_T$</th>
<th>QCD $\frac{d\sigma}{dp_T}$</th>
<th>$W'$ $\frac{d\sigma}{dp_T}$</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>[TeV]</td>
<td>[fb/GeV]</td>
<td>[fb/GeV]</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>$10^3$</td>
<td>$10^{-1}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>1.0</td>
<td>$10$</td>
<td>$10^{-3}$</td>
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</tr>
</tbody>
</table>

- Rough order of magnitude differential cross sections taken from MC show the extent of the problem, 1 signal in 10k background events
- **Obvious problem** when you look at the raw events selected by the jet trigger used in the analysis
- Our jet substructure thresher has quite the haystack against it
Tools at our disposal

- What do we have to remove the QCD background?

1. The BDRS-A filtered CA $R = 1.2$ jets
   - Selects two (three) pronged decays within jets

2. Filtered jet mass
   - Separates peaked boson mass from falling QCD spectrum

3. Subjet momentum balance
   - Boson jets symmetric, QCD unbalanced

4. Number of tracks ghost matched to the unfiltered jet
   - More hadronic activity in QCD jets
Tools: Jet mass

2 Filtered jet mass
   - Separates peaked boson mass from falling QCD spectrum

   - Apply ±13 GeV **window cuts** around boson mass from MC simulation peak ($m_W = 82.4$, $m_Z = 92.8$)

   - For example, in the $WZ$ cut:
     - Leading mass jet
       $79.8 \text{ GeV} < m_{\text{jet}} < 105.8 \text{ GeV}$
     - Subleading mass jet
       $69.4 \text{ GeV} < m_{\text{jet}} < 95.4 \text{ GeV}$

   - **Very powerful** cut!
     - $\epsilon_{\text{signal}} \approx 80\%$
     - $\epsilon_{\text{background}} \approx 10 - 15\%$

   - Cuts optimised using a **data CR**
     - Dijet formed from two tagged/un-tagged regions

   - N.B. **Windows overlap!!!**
Subjet momentum balance

- Boson jets **symmetric**, QCD **unbalanced**

- $W/Z \rightarrow q\bar{q}$ decays tend to share momentum **equally** between decay products

- **Soft gluon** radiation leads to asymmetric splittings

- Apply a more stringent $\sqrt{y} \geq 0.45$ cut on the subjet momentum balance

- Another **powerful** cut!
  - $\epsilon_{\text{signal}} \approx 70\%$
  - $\epsilon_{\text{background}} \approx 30\%$

- Cuts optimised using **MC**, using a wide mass window, $60 \text{ GeV} < m_{\text{jet}} < 110 \text{ GeV}$
Number of tracks ghost matched to the unfiltered jet

- More hadronic activity in QCD jets

- Emission of hard gluon dominates after mass/asymmetry cuts

- Expect increased hadronic activity from gluon

- Use the number of ghost associated ungroomed tracks, \( n_{\text{trk}} \), as a proxy for hadronic activity, [arXiv:0802.1188]

- Apply \( n_{\text{trk}} \leq 30 \) cut

- Efficiency after mass/asymmetry
  
  - \( \epsilon_{\text{signal}} = 83 \pm 7\% \)
  
  - \( \epsilon_{\text{background}} \approx 65\% \)

- Very hard to model in MC

- Cuts optimised using V+jets enriched data CR

- Efficiency calibrated in this CR

\( \sqrt{s} = 8 \text{ TeV} \)
Event selection: Putting it all together

1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply BDRS-A split-filter
3. Require $m_{jj} > 1.05$ TeV
   - Ensures on trigger plateau
4. **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
   - s-channel signal more central than t-channel QCD
5. Leading jets $p_T$ asymmetry $A_{p_T} < 0.15$
   - Used as proxy for large-R jet cleaning
6. Leading jets $|\eta| < 2.0$
   - Ensures a good overlap with tracker
7. Correction for jets on calorimetry holes
8. **Boson tagging** cuts
   - Jet mass ($WZ, WW, ZZ$), momentum balance, $n_{trk}$
   - Background efficiencies
     - Topological $\epsilon \approx 48\%$
     - Tagger $\epsilon \approx 1.2 - 0.6\%$

---

**ATLAS**
$s = 8$ TeV, 20.3 fb$^{-1}$

**Significance**

- Data
- Background model
- Significance (stat)
- Significance (stat + syst)

No boson tagging

$X \rightarrow VV \rightarrow JJ$
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**ATLAS Simulation**

$\sqrt{s} = 8$ TeV

- EGM $W^\pm \rightarrow WZ$
- Bulk $G_{RS} \rightarrow WW$
- Bulk $G_{RS} \rightarrow ZZ$

Event topology requirements

- Resonance Mass [TeV]
  - 1.4
  - 1.6
  - 1.8
  - 2
  - 2.2
  - 2.4
  - 2.6
  - 2.8

Selection efficiency

- ATLAS Simulation
  - Topological $\epsilon \approx 48\%$
  - Tagger $\epsilon \approx 1.2 - 0.6\%$

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Event topology and boson tagging requirements

- Resonance Mass [TeV]
  - 1.4
  - 1.6
  - 1.8
  - 2
  - 2.2
  - 2.4
  - 2.6
  - 2.8

Selection efficiency
Modelling the Background

- After trying to kill the background we now arrive at the point of modelling it.
- MC statistics needed to properly model the high $m_{JJ}$ tail are prohibitively large.

- Assume a steeply and smoothly falling distribution models the background.
- Any resonance should be narrow, thus only affect a few bins.
- Use a parametric function to model the background from the data

$$\frac{dn}{dx} = p_1 (1 - x)^{p_2 - \xi p_3} x^{p_3}$$

Where,
- $x = m_{JJ}/\sqrt{s}$
- $m_{JJ}$ is the dijet invariant mass,
- $p_1$ is a normalisation factor,
- $p_2$ and $p_3$ are dimensionless shape parameters,
- $\xi$ is a dimensionless constant chosen after fitting to minimise the correlations between $p_2$ and $p_3$. 

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Alternate fit functions give **similar** results.

Error taken from errors on **functional** parameters.

Fit tested on,

- Raw data
- **PYTHIA**/**HERWIG** MC
- Mass sideband data CRs
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  \]
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  - Raw data
  - Pythia/Herwig MC
  - Mass **sideband** data CRs

---

**Sample**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\chi^2$/nDOF</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia dijet events</td>
<td>24.6/22</td>
<td>0.31</td>
</tr>
<tr>
<td>Herwig++ dijet events</td>
<td>15.9/22</td>
<td>0.82</td>
</tr>
<tr>
<td>Data with $110 &lt; m_{j1} \leq 140$ GeV and $40 &lt; m_{j2} \leq 60$ GeV</td>
<td>12.1/11</td>
<td>0.79</td>
</tr>
<tr>
<td>Data with $40 &lt; m_{j} \leq 60$ GeV for both jets</td>
<td>19.8/13</td>
<td>0.56</td>
</tr>
<tr>
<td>Data with $110 &lt; m_{j} \leq 140$ GeV for both jets</td>
<td>5.0/6</td>
<td>0.91</td>
</tr>
</tbody>
</table>
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  \[
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Assume a **steeply** and **smoothly falling** distribution models the background

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Use a **parametric function** to model the background from the data

$$\frac{dN}{dx} = p_1 (1 - x)^{p_2 - \xi p_3} x^{p_3}$$

Alternate fit functions give **similar** results

Error taken from errors on **functional parameters**

Fit tested on,

- Raw data
- **PYTHIA**/**HERWIG** MC
- Mass **sideband** data CRs

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\chi^2$/nDOF</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA dijet events</td>
<td>24.6/22</td>
<td>0.31</td>
</tr>
<tr>
<td>HERWIG++ dijet events</td>
<td>15.9/22</td>
<td>0.82</td>
</tr>
<tr>
<td>Data with $110 &lt; m_{j1} \leq 140$ GeV and $40 &lt; m_{j2} \leq 60$ GeV</td>
<td>12.1/11</td>
<td>0.79</td>
</tr>
<tr>
<td>Data with $40 &lt; m_{j1} \leq 60$ GeV for both jets</td>
<td>19.8/13</td>
<td>0.56</td>
</tr>
<tr>
<td>Data with $110 &lt; m_{j} \leq 140$ GeV for both jets</td>
<td>5.0/6</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Systematic uncertainties: Shape

- **Background**: Taken from the uncertainties on the *fit parameters*
- **Signal**: Various systematics affect the signal *reconstruction* and *selection efficiency*

**Shape systematics:**
- The jet $p_T$ and jet mass scale uncertainties determined by the *track/calo double ratio* technique
- For example for a variable $x$,
  \[
  \frac{\chi_{\text{data}}^{\text{track}}/\chi_{\text{data}}^{\text{calo}}}{\chi_{\text{MC}}^{\text{track}}/\chi_{\text{MC}}^{\text{calo}}}
  \]
- Applied as a Gaussian with $\mu = 1$ and $\sigma$ equal to the *observed uncertainty*
  - jet $p_T$ scale: 2%
  - jet mass scale: 3%
- An uncertainty on the jet $p_T$ resolution of 20% is applied as an additional *smearing* on top of the nominal 5%

---

### Source Uncertainty Constraining pdf

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>Constraining pdf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet $p_T$ scale</td>
<td>2%</td>
<td>$G(\alpha_{PT}</td>
</tr>
<tr>
<td>Jet $p_T$ resolution</td>
<td>20%</td>
<td>$G(\sigma_r E</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>3%</td>
<td>$G(\alpha_m</td>
</tr>
</tbody>
</table>

**ATLAS Simulation**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$W'(1.4$ TeV$) \rightarrow WZ \rightarrow qqqq$

$\Delta y_y < 1.2$

$\Delta y_y < 2.0$

$A < 2.0$

$|\eta| < 0.15$

$\tilde{y}_f = 0.45$

$n_{trk} < 30$

$x \rightarrow VV \rightarrow JJ$
**Systematic uncertainties: Normalisation**

- **Background**: Taken from the uncertainties on the fit parameters
- **Signal**: Various systematics affect the signal reconstruction and selection efficiency
- **Normalisation systematics**: Large uncertainty on the $n_{\text{trk}}$ cut evaluated in the data driven $V$+jets study used to define the efficiency of the cut
- Jet mass scale affects both shape and normalisation strongly
- $\sqrt{y}$ scale evaluated using the double ratio method
- Resolutions taken as 20% smearings
- **Shower model** evaluated by comparing MC showered by PYTHIA or HERWIG
- **PDF4LHC** method used to evaluate PDF uncertainties
- ATLAS luminosity uncertainty assumed

---

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of the track-multiplicity cut</td>
<td>20.0%</td>
</tr>
<tr>
<td>Jet mass scale</td>
<td>5.0%</td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td>5.5%</td>
</tr>
<tr>
<td>Subjet momentum-balance scale</td>
<td>3.5%</td>
</tr>
<tr>
<td>Subjet momentum-balance resolution</td>
<td>2.0%</td>
</tr>
<tr>
<td>Parton shower model</td>
<td>5.0%</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>3.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
</tr>
</tbody>
</table>

---

$X \rightarrow VV \rightarrow JJ$
The long and winding road....

OK, enough with the build-up.....

What does the triggered data look like after applying our selection???
Full WZ selection applied to the data
- Z mass window applied to leading mass jet
- W mass window applied to sub-leading mass jet

Good agreement seen with steeply, smoothly falling background model in the low/high mass regions

Deviation from the background observed at around 2 TeV

Benchmark extended gauge model W' signal MC shown for comparison purposes
Full **WW** selection applied to the data

- **W** mass window applied to **both** jets

**Good agreement** again seen with steeply, smoothly falling background model

**Deviation** from the background still observed at around 2 TeV

**Remember:** There is an overlap between the **W/Z** mass windows (≈ 20%)

**Benchmark** Bulk Randall-Sundrum graviton signal MC shown for comparison purposes
Full ZZ selection applied to the data
- Z mass window applied to both jets

Good agreement again seen with steeply, smoothly falling background model

Deviation from the background still observed at around 2 TeV

Remember: There is an overlap between the W/Z mass windows (≈ 20%)

Benchmark Bulk Randall-Sundrum graviton signal MC shown for comparison purposes
What do these events look like? Dramatic!
What do these events look like? Energetic!
Digging deeper into the jets....

These jet event displays take a bit more explanation, but offer a powerful insight into the analysis jets

- The ATLAS detector volume is shown unfolded in $\eta$ and $\phi$

- Inner detector track positions are shown as crosses
  - Black Tracks: From primary vertex
  - Blue Tracks: From secondary vertices

- Calorimeter deposits are displayed on the rainbow scale

- The outlines of the CA 1.2 jets are shown
  - Black: Leading $p_T$ jet
  - Mauve: Sub-leading jet

- Grey area: Sub-jets after filtering
Digging deeper into the jets....

ATLAS
\( \sqrt{s} = 8 \text{ TeV} \)
Run: 201556 Event: 7295269

ATLAS
\( \sqrt{s} = 8 \text{ TeV} \)
Run: 201489 Event: 75855145

What do we see here?

- Subjets are highly collimated
- PV tracks are highly correlated with the selected sub-jets
- Energy deposits concentrated in the sub-jet
- Pile-up tracks/deposits sparsely distributed over the events
- Successfully picked the boson out of the pileup?

\[ X \rightarrow VV \rightarrow JJ \]
Time to cross-check.....

- Deviations from the expected background, especially ones at the tail of the data distribution, mean one thing for physicists....
  - What on Earth did we do wrong?
- Try to evaluate any possible issues with the analysis
- Operation Cross-check begins
- Look for mistakes, bugs or shaping effects in:
  - Detector/data taking effects
  - Jet reconstruction effects
  - Event selection effects

**ATLAS**

**WZ Selection**

**WW Selection**

**ZZ Selection**
Time to cross-check.....

From E. Kajomovitz
Time to cross-check.....

- Started trawling through SR/CR kinematic distributions, looking for unusual features in the signal regions
- Look at the effect of single cuts on the distribution
- Look at the effect of $N - 1$ cuts on the distribution
  - Is one cut driving all of the deviation?
- Many, many, many..... more, you can only get so much approved...
Time to cross-check.....

- Started trawling through SR/CR kinematic distributions, looking for unusual features in the signal regions.
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**Time to cross-check.....**

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  - Is one cut driving all of the deviation?
- Many, many, many..... more, you can only get so much approved...

---

**ATLAS**

- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- Data
- Background model
- 2.0 TeV EGM W$'$, $c = 1$
- Significance (stat + syst)

**WZ Selection**

- $\rightarrow VV \rightarrow JJ$
Did we find any errors?

- In so many cross-checks, yes, bugs were found and fixed
- Always attempted to shield the data from any possible biases by using control regions to test
- After almost a year and a half of scrutiny by the analysers/Exotics group/ATLAS we found no major issues
- Therefore we continue to publish the final results
- Run-2 was looming!
A discrepancy was seen with respect to the expected background distribution.

Once suitably confident it is not an error, its significance should be quantified.

In the WZ channel:
- Local $p_0 = 3.4\sigma$
- Global $p_0 = 2.5\sigma$

Global $\sigma$ takes into account the look elsewhere effect.

LEE includes weighted contribution from WW/ZZ channels due to the overlap.

Therefore, no statistically significant deviation from the background has been observed.
As no significant deviation was observed, we continue to set limits on the observed distributions.

95\% confidence limits set on $\sigma \times B$ using the CL$_S$ prescription taking into account the systematic uncertainties and background fit.

Expected limits broadly agree with the observed limits.

Exclusion of EGM $W'$ from 1.3 – 1.5 TeV.

Broad deviation from the background observable at around 2 TeV.

Benchmark extended gauge model $W' \sigma \times B$ shown for comparison purposes.
As no significant deviation was observed, we continue to set limits on the observed distributions.

95% confidence limits set on $\sigma \times B$ using the CL$_S$ prescription taking into account the systematic uncertainties and background fit.

**Expected** limits broadly agree with the observed limits.

**Exclusion** of graviton production at no masses.

**Deviation** from the background observable at around 2.1 TeV.

**Benchmark** Bulk Randall-Sundrum graviton $\sigma \times B$ shown for comparison purposes.
As no significant deviation was observed, we continue to set limits on the observed distributions.

95% confidence limits set on $\sigma \times B$ using the CL$_S$ prescription taking into account the systematic uncertainties and background fit.

- **Expected** limits broadly agree with the observed limits.
- **Exclusion** of graviton production at no masses.
- **Broad deviation** from the background observable at around 2 TeV.
- **Benchmark** Bulk Randall-Sundrum graviton $\sigma \times B$ shown for comparison purposes.

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$\sigma(pp \rightarrow G_{RS} \rightarrow ZZ) \times BR(G_{RS} \rightarrow ZZ)$ [fb]
Are we alone? ATLAS searches

ATLAS
\[ \sqrt{s} = 8 \text{ TeV}, \int L \, dt = 20.3 \text{ fb}^{-1} \]

- ATLAS resolved dijet search [arXiv:1407.1376], nothing seen ✗
- ATLAS semi-leptonic search \(W(l\nu)Z(jj)\) [arXiv:http://1503.04677], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ✗
- ATLAS semi-leptonic search \(W(jj)Z(\ell\ell)\) [arXiv:1409.6190], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ✗
Are we alone? ATLAS searches

ATLAS

\( \sqrt{s} = 8\, \text{TeV}, \int L dt = 20.3\, \text{fb}^{-1} \)

\( W \rightarrow l \nu + \geq 1\) large-R jet

- Data
- \( W/Z + \text{jets} \)
- \( t\bar{t} + \text{single top} \)
- Multijet
- Diboson
- Uncertainty
- \( G^*(1200\, \text{GeV}) \)
- \( W'(1200\, \text{GeV}) \)

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Are we alone? Across the ring....CMS

- CMS dijet search [arXiv:1501.04198], blip in 2-btag at 2 TeV? Trick of the eye? 
  ![Graph](graph.png)

- CMS $W_R$ search [arXiv:1407.3683], excess at 2 TeV in $eejj$ channel only
- CMS $WW/WZ/ZZ$ semi-leptonic search [arXiv:1405.3447], in tails/nothing seen
- CMS $WW/WZ/ZZ$ fully hadronic search [arXiv:1405.3447], uses n-subjettiness, broad blip at 2 TeV
Are we alone? Across the ring....CMS

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CMS \( WW/WZ/ZZ \) fully hadronic search [arXiv:1405.3447], uses n-subjettiness, broad blip at 2TeV ✗✓
The Future Now: Data is here!

Fun fact: The Run-1 paper was submitted around 13 hours before the first collisions of Run-2
How much data is needed?

So question one is **how much** Run-2 13 TeV data do we need to **surpass** the Run-1 result?

- At 2 TeV production cross-sections grow considerably
  - For gluon-gluon fusion \( \times 15 \), i.e. for \( G_{RS} \) production
  - For \( q\bar{q} \) initiated \( \times 8 \), i.e. for \( W' \) production
  - Unfortunately QCD background also increases

- So a **smaller** amount of Run-2 data \((1 - 3 fb^{-1})\) is should be roughly equivalent to the 8 TeV dataset
So question one is **how much** Run-2 13 TeV data do we need to **surpass** the Run-1 result?

At 2 TeV production cross-sections grow **considerably**

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- For $q\bar{q}$ initiated $\times 8$, i.e. for $W'$ production
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- For $q\bar{q}$ initiated $\times 8$, i.e. for $W'$ production
- Unfortunately QCD background also increases

So a **smaller** amount of Run-2 data ($1 - 3 fb^{-1}$) is should be roughly equivalent to the 8 TeV dataset
How much data is needed?

- **What local \( \sigma \) values can we see assuming**
  - Different 13 TeV recorded luminosity points
  - Systematics size w.r.t. Run-1
  - Injecting a signal with a cross-section the size of the discrepancy seen in Run-1

- **If realised** in nature, observation should be possible even with the reduced 2015 data expectations

- Semi-leptonic channels can **control backgrounds** more easily (mostly \( V+\text{jets} \))

- Should have an **equivalent reach** at 2 TeV to the fully hadronic channel in Run-2!

- Hadronic channel will still be **more competitive** at the highest masses
Ready for data?

- New ATLAS data format, xAOD working ✓
- Physics derivations, DxAOD, running ✓
  - On MC ✓
  - On data ✓
- CxAOD analysis framework in place ✓
- ResonanceFinder statistical framework in place ✓
- New R2D2 boosted boson tagger defined ✓
  - No really... \( R = 0.2 \) subjet, \( D_2^\beta \) substructure variable
  - [arXiv:1409.6298]
- Ready, to improve the analysis with new techniques and data YES! ✓
- Steady, to push search to higher masses YES!! ✓
- Go, to confirm/disprove excess YES!!! ✓
Presented a search for a **high mass diboson resonance**
- Used 20.3 fb$^{-1}$ 8TeV ATLAS data
- Jet substructure (BDRS-A CA 1.2 jets) used to separate signal from background
- QCD dominated background modelled by parametric function

**Deviation** from expected steeply, smoothly falling background seen at 2 TeV

Cross-checks performed, **no major issues** discovered

**Excess** $\rho_0 = 3.4\sigma$ local, 2.5$\sigma$ global

**Limits** exclude EGM $W'$ models with $1.3 < m_{W'} < 1.5$ TeV

**Preparations** underway to repeat search in 13TeV data
Backup

Undo jet
Reject constituents

Find hard splitting

Filter constituents

X → VV → JJ
A data CR was formed from two tagged/untagged samples

A wide mass window \((40 < m_J < 400 \text{ GeV})\) used

1. CR A: Leading jet tagged, sub-leading fails tag
2. CR B: Leading jet fails tag, sub-leading passes tag

Forms dijet sample by taking one jet from CR A and one from CR B

Use this as a high stats QCD region for comparison with signal MC

Compute mass window efficiencies as function of window width for different \(W'\) masses

\[
\begin{array}{c|c|c|c}
\text{ATLAS Simulation} & 8 \text{ TeV}, 20.3 \text{fb}^{-1} \\
\hline
\text{For } W(1.4 \text{ TeV}) &\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{ATLAS Simulation} & 8 \text{ TeV}, 20.3 \text{fb}^{-1} \\
\hline
\text{For } W(1.8 \text{ TeV}) &\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{ATLAS Simulation} & 8 \text{ TeV}, 20.3 \text{fb}^{-1} \\
\hline
\text{For } W(2.2 \text{ TeV}) &\end{array}
\]
$n_{\text{trk}}$ optimisation

- $n_{\text{trk}}$ is poorly modelled in MC
- Cannot trust it to optimise cut or measure its efficiency
- Select $V+$jets enriched data sample
  1. Optimise the cut by fitting QCD background vs selected signal peak
  2. Measure the efficiency of selected cut in data sample
- Two models used to fit background in this region
- Both fit well, efficiency error taken from a combined PDF of both fits
Systematic variations

**ATLAS Simulation**  
\(\sqrt{s} = 8 \text{ TeV}, \quad 20.3 \text{fb}^{-1}\)

- **BDRS-A**  
  \(|\eta| < 1.2\)  
  \(|\eta| < 2.0\)  
  \(A < 0.15\)  
  \(|n_{\text{trk}}| > 0.45\)  
  \(n_{\text{trk}} < 30\)

- **W(1.4 TeV) \rightarrow WZ \rightarrow qqqq**

**Nominal**  
- **JMS up**  
- **JMS down**  
- **JMR**

**ATLAS Simulation**  
\(\sqrt{s} = 8 \text{ TeV}, \quad 20.3 \text{fb}^{-1}\)

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\(\sqrt{s} = 8 \text{ TeV}, \quad 20.3 \text{fb}^{-1}\)

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  \(|\eta| < 1.2\)  
  \(|\eta| < 2.0\)  
  \(A < 0.15\)  
  \(|n_{\text{trk}}| > 0.45\)  
  \(n_{\text{trk}} < 30\)

- **W(1.8 TeV) \rightarrow WZ \rightarrow qqqq**

**Nominal**  
- **JMS up**  
- **JMS down**  
- **JMR**

**ATLAS Simulation**  
\(\sqrt{s} = 8 \text{ TeV}, \quad 20.3 \text{fb}^{-1}\)

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  \(|\eta| < 2.0\)  
  \(A < 0.15\)  
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  \(n_{\text{trk}} < 30\)

- **W(2.2 TeV) \rightarrow WZ \rightarrow qqqq**

**Nominal**  
- **JMS up**  
- **JMS down**  
- **JMR**
Comparing the effect of applying all signal selections at once, and the same flavour selections at once.

**ATLAS**

- **data**
- **background model**
- **significance (stat)**
- **significance (stat + syst)**

**WW+ZZ+WZ Selection**

- Events / 100 GeV
- Significance

**WW Selection**

- Events / 100 GeV
- Significance

**ZZ Selection**

- Events / 100 GeV
- Significance

**1.5 TeV**

- PI
- $k/R_s$

**2.0 TeV**

- PI
- $k/R_s$

**Bulk G**

- PI
- $k/R_s$
The resonance width ($\Gamma$) and the product of cross sections and branching ratios (BR) to four-quark final states used in modelling $W' \to WZ$, $G_{RS} \to WW$, and $G_{RS} \to ZZ$, for several values of resonance pole masses ($m$). The fraction of events in which the invariant mass of the $W'$ or $G_{RS}$ decay products lies within 10% of the nominal resonance mass ($f_{10\%}$) is also displayed.

<table>
<thead>
<tr>
<th>$m$ [TeV]</th>
<th>$\Gamma_{W'}$ [GeV]</th>
<th>$\Gamma_{G_{RS}}$ [GeV]</th>
<th>$W' \to WZ$</th>
<th>$G_{RS} \to WW$</th>
<th>$G_{RS} \to ZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma \times BR$ [fb]</td>
<td>$f_{10%}$</td>
<td>$\sigma \times BR$ [fb]</td>
<td>$f_{10%}$</td>
<td>$\sigma \times BR$ [fb]</td>
</tr>
<tr>
<td>1.3</td>
<td>47</td>
<td>76</td>
<td>19.1</td>
<td>0.83</td>
<td>0.73</td>
</tr>
<tr>
<td>1.6</td>
<td>58</td>
<td>96</td>
<td>6.04</td>
<td>0.79</td>
<td>0.14</td>
</tr>
<tr>
<td>2.0</td>
<td>72</td>
<td>123</td>
<td>1.50</td>
<td>0.72</td>
<td>0.022</td>
</tr>
<tr>
<td>2.5</td>
<td>91</td>
<td>155</td>
<td>0.31</td>
<td>0.54</td>
<td>0.0025</td>
</tr>
<tr>
<td>3.0</td>
<td>109</td>
<td>187</td>
<td>0.088</td>
<td>0.31</td>
<td>0.00034</td>
</tr>
</tbody>
</table>
The resonance width ($\Gamma$) and the product of cross sections and branching ratios (BR) to four-quark final states used in modelling $W' \rightarrow WZ$, $G_{RS} \rightarrow WW$, and $G_{RS} \rightarrow ZZ$, for several values of resonance pole masses ($m$). The fraction of events in which the invariant mass of the $W'$ or $G_{RS}$ decay products lies within 10% of the nominal resonance mass ($f_{10\%}$) is also displayed.

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<th>$\Gamma_{G_{RS}}$ [GeV]</th>
<th>$W' \rightarrow WZ$ $\sigma \times \text{BR}$ [fb]</th>
<th>$f_{10%}$</th>
<th>$G_{RS} \rightarrow WW$ $\sigma \times \text{BR}$ [fb]</th>
<th>$f_{10%}$</th>
<th>$G_{RS} \rightarrow ZZ$ $\sigma \times \text{BR}$ [fb]</th>
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<tr>
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Number of events observed in the WZ, WW, and ZZ selected samples in each dijet mass bin used in the analysis, compared to the prediction of the background-only fit.

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### Observed and expected limits on the EGM $W'$ models in the $WZ$ selection

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