Searching for Di-boson resonances at the edge of the LHC

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Theory Seminar ULB September 18th 2015
Diboson resonances at the edge of the LHC

- Diboson resonances appear in many theories extending the SM
  - Simple benchmarks
  - Extended gauge sector models ($W' \rightarrow WZ$)
  - Extra dimensions Models ($G \rightarrow WW, ZZ$)

- We want to explore the high energy edge of the LHC
  - Leptonic decays suffer from low branching ratios
  - Hadronic decays suffer from large backgrounds and require special reconstruction techniques
  - Still... for resonances $O$(TeV) the cross section is so small that we want to take advantage of the large BR

- The challenge - **hadronic decays**!

<table>
<thead>
<tr>
<th>Boson decay fractions</th>
<th>$W$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell \nu, \ell \ell$</td>
<td>22%</td>
<td>7%</td>
</tr>
<tr>
<td>$\tau \nu, \tau \tau$</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>$\nu \nu$</td>
<td>-</td>
<td>20%</td>
</tr>
<tr>
<td>$qq$</td>
<td>67%</td>
<td>70%</td>
</tr>
</tbody>
</table>
Naïve approach to search for Diboson resonances with hadronic decays

1-quark $\rightarrow$ 1 jet

Jet

Clustering algorithm

Energy deposits

Hadron decay

Hadronization

Parton shower

#Events vs. $M_{4jets}$

$\sqrt{s}$
At the edge bosons are boosted

The vector bosons have masses of $O(100 \text{ GeV})$

So most of the $O(\text{TeV})$ mass of the resonance transforms into large boost to the decaying products

In a decay like this we would have each boson with a momentum of the $O(\text{TeV})$!
Things are different at large boosts

“Natural” angular separation:
\[ dR \sim \frac{2m}{(p_T)} \]
Normal jet clustering parameter \( R=0.4 \)

- Resolved Regime: **Two jets**
  The boson has relatively low momentum in the lab frame so we are able to reconstruct one jet for each quark

- Boosted Regime: **Single boson jet**
  The boson has high momentum in the lab frame - the outgoing quarks are very close to each other so the jets begin to merge

\[ P_T \sim O(100\text{GeV}) \]
Ultimate challenge - beat the QCD background

\[
\frac{d\sigma}{p_T} \times BR \text{ (rough numbers)}^* \\
\begin{array}{|c|c|c|}
\hline
\text{Leading Jet [GeV]} & \text{QCD [fb/GeV]} & \text{W'} [fb/GeV] \\
\hline
0.5 \text{ TeV (1.2 TeV W')} & 10^3 & 10^{-1} \\
1.0 \text{ TeV (2 TeV W')} & 10 & 10^{-3} \\
\hline
\end{array}
\]

Discovering Toolkit

E. Kajomovitz, Duke
Outline

- Tagging Boson Jets
- Searches for Heavy Diboson resonances with ATLAS at $\sqrt{s} = 8$ TeV
  - In depth look at the fully hadronic channel
  - Channels with leptons
  - Putting it all together
- What to expect
Tagging Boson Jets
### Boson vs QCD jets

#### Boson Jets
- **Boson decay**
  - Two narrow regions with high energy density corresponding to each quark
  - Each of the quarks carries comparable fraction of the boson momentum in the lab frame
  - Mass of the jet comes from the addition of the two regions corresponding to the quarks

#### QCD Jets
- **High-pT parton**
  - Narrow region with high energy density
  - High energy density region has most of the momentum of the jet
  - Mass of the jet from the spread of the energy of the high pT parton
Fat-jet – Grooming – Tagging

1. **Fat-jet**
   - Large distance parameter to pick up all radiation from original decay

2. **Grooming**
   - Signal – Take out jet constituents that don’t belong to the signal decay
   - Background – Preserve background characteristics in the jet

3. **Tagging**
   - Use differences in Signal and Background jet characteristics to reject background jets
Fat jet

C/A Clustering
1) Smaller distance first
2) Merge if distance smaller than $R = 1.2$
3) Iterate until nothing to merge

BOSON
Angular separation – merged late
Collimated structure – merged early

QCD
Angular separation – merged late
Collimated structure – merged early
Mass Drop Grooming

**Mass Drop Filter**

1) Go back in clustering
2) Find point where momentum is balanced amongst proto jets and mass of proto jets is small compared to merged jet

*B Only most important details for large boosts*
Sub-jet momentum balance after grooming

\[ \sqrt{s} = 8 \text{ TeV} \]

**ATLAS Simulation**

EGM \( W' \to WZ \) (\( m_{W'} = 1.8 \text{ TeV} \))

- \(|\Delta y_{jj}| < 1.2\)
- \(|\eta_j| < 2\)
- \(1.62 \leq m_{jj} < 1.98 \text{ TeV}\)
- \(60 \leq m_j < 110 \text{ GeV}\)

Pythia QCD dijet
Jet mass after grooming

\[ \frac{\text{Fraction of jets}}{	ext{5.0 GeV}} \]

- **ATLAS Simulation**
  - bulk $G_{RS} \to WW (m_G = 1.8 \text{ TeV})$
  - bulk $G_{RS} \to ZZ (m_G = 1.8 \text{ TeV})$
  - Pythia QCD dijet

**Criteria**
- $|\Delta y_{jj}| < 1.2$
- $|\eta_j| < 2$
- $1.62 \leq m_{jj} < 1.98 \text{ TeV}$
- $|y| > 0.45$
Other handles for discrimination – Hadronic activity

- We’ve applied selection criteria based on the jet mass and momentum balance
- Remaining background is enriched with gluon splitting jets
  - Increased hadronic activity
- Use number of tracks associated to the jet as a proxy
Data driven estimate of the $n_{\text{trk}}$ selection efficiency

- Monte Carlo simulations of $n_{\text{trk}}$ predict a good discriminating power to distinguish between boson jets and the background for this variable

- However, the simulation is not precise enough to determine the efficiency and background rejection to the necessary accuracy

- Use a control region in data to determine the properties of a selection requirement on this variable
  - Select a W/Z+jets enriched sample by selecting those events with a jet passing the boson selection criteria on the sub-jet momentum balance
  - Use the jet mass distribution to determine the relative signal efficiency of a cut on $n_{\text{trk}}$
  - Dominant uncertainty is the mass distribution of the background

**Control Region**

*W/Z+jets enriched sample*

![Jet mass distribution](image)

**ATLAS**

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

$n_{\text{trk}} < 30$, Third deg. polynomial
Tagging “Boson Jets”

Jet Mass:
- Boson jet mass peaks at nominal boson mass
- QCD mostly falling mass distribution

Momentum balance:
- For boson jets the subjets have comparable momenta at the stopping point
- For QCD jets one of the subjets will have most of the momentum

Hadronic activity:
- Increased hadronic activity in gluon-like jets

For each search channel the optimal tagging point will depend on the backgrounds
Boson tagged jets in data

Figure 24:
Jet display for Event 5303984 in Run 203027. The colored boxes represent the topological clusters, the blue crosses represent tracks not associated with the event primary vertex, the black crosses represent tracks associated with the event primary vertex, and the gray areas are the reclustered jets kept after the filtering algorithm.

$ATLAS \sqrt{s} = 8 \text{ TeV}$

Run: 203027 Event: 5303984

$p_T^1 = 999.3 \text{ GeV}; \phi_1 = 0.70; m_1 = 89.2; n_{\text{trk}1} = 29; p_T^2 = 999.3 \text{ GeV}; \phi_2 = 0.05; m_2 = 72.3; n_{\text{trk}2} = 23; m_{jj} = 2068.6 \text{ GeV}.$

Figure 25:
Jet display for Event 7295269 in Run 201556. The colored boxes represent the topological clusters, the blue crosses represent tracks not associated with the event primary vertex, the black crosses represent tracks associated with the event primary vertex, and the gray areas are the reclustered jets kept after the filtering algorithm.

$p_T^1 = 950.3 \text{ GeV}; \phi_1 = 0.67; m_1 = 89.1; n_{\text{trk}1} = 14; p_T^2 = 909.4 \text{ GeV}; \phi_2 = 0.06; m_2 = 103.1; n_{\text{trk}2} = 26; m_{jj} = 1955.2 \text{ GeV}.$
Searching for diboson resonances: In depth look at the fully hadronic channel

arxiv:1506.00962
Fully hadronic channel

- **Huge backgrounds!** - Apply a **tight** tagging selection
  - Different narrow jet mass windows for selecting W or Z
  - Simple strategy optimized for model rejection
  - Considerable overlap between the windows

- Backgrounds are so large that additional handles are needed
  - Event topology

- Additional selection criteria dictated / driven by detector considerations
Event topology

Jets tend to go more “forward”
Rapidity difference between jets has higher probability to be large

Jets tend to go more “central”
Rapidity difference between jets has higher probability to be small

Figure 12: The difference in rapidity between the leading and subleading jet, for simulated $W'$ and dijet background events passing the trigger and mass-drop filtering requirements, for four values of the $W'$ boson mass and corresponding dijet mass selections. The $W'$ signal yield has been scaled for visibility, as indicated in each figure.
Additional requirements

Pseudo rapidity requirement

\[
|\Delta y| < 1.2 \\
1.26 \leq m_j < 1.54 \text{ TeV}
\]

\[
\frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})} < 0.35
\]

\[
\frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})} \leq 0.3
\]
Estimating the background

- Dominant background are dijet events from QCD processes
  - Simulation is not accurate enough to provide a robust prediction for estimating the background

- Data driven estimate
  - Smoothly and steeply falling distribution for backgrounds
  - Signal is narrow (only a small region is affected by the presence of a signal)
  - Fit a parametric shape to the data

- For the parameterization we need to ensure
  - Has adequate complexity
  - Will not produce fake signals

\[
\frac{dn}{dx} = p_1(1 - x)^{p_2 + \xi p_3} x^{p_3}
\]
Tests on background parameterization

- Two types of tests
  - *Spurious* signal: Fit S+B in background only distributions and best fit signal is small compared to background uncertainty
  - Parameterization complexity: Adding additional parameters does not result in a significant better fit

- Test parameterization in control regions
  - Sidebands in data
  - Untagged data
  - Mixture of sideband spectra

- Test parameterization in background simulations
  - Different dijet simulation
  - Consider large variations in the background composition

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Diagram 1: Fits of the background model to the dijet mass for ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Diagram 2: Comparison of data and background model significances for ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
In most of the range there is good agreement between the background estimate and the observed data.

At ~2 TeV the three channels (WW/WZ/ZZ) observe statistically mild deviations from the background. Approximately 20% of the events are shared in the three signal regions. Overlap between WW/WZ or WZ/ZZ is larger.

Largest deviation is in the WZ channel 2.5 sigma global (3.4 local)
Channels with leptons in ATLAS

ATLAS-CONF-2015-045 (Combination)
arXiv:1406.4456 (lvll)
arXiv:1409.6190 (llqq)
arXiv:1503.04677 (lvqq)

Figure 1: The signal acceptance times efficiency for the different analyses entering the combination are shown in (a) for the EGM W' model and in (b) for the bulk G* model. The error bands represent the combined statistical and systematic uncertainties.

6 Systematic uncertainties

The sources of systematic uncertainties along with their effects on the expected signal and background yields for each of the individual channels used in this combination are described in detail in their corresponding publications [17,19–21]. Although the results from the different search channels in this combination are statistically independent, commonalities between the different search channels, such as the objects used, the signal and background simulation, and the integrated luminosity estimate, introduce correlated effects in the signal and background expectations. Whenever an effect due to an uncertainty in the triggering, identification, or reconstruction of leptons is considered for a channel, it is treated as fully correlated with the effects due to this uncertainty in other channels. In the same manner, the effects of each uncertainty related to the small-R jet energy scale and resolution are treated as fully correlated in all channels using small-R jets or \(E_{\text{miss}}\). For the search channels using large-R jets, uncertainties in the large-R jet energy scale, energy resolution, mass scale, mass resolution, or in the modeling of the boson tagging discriminant are taken as fully correlated. Uncertainties in the data-driven background estimates are treated as uncorrelated. The effects of uncertainty in the initial and final state radiation (ISR and FSR) modeling and in the PDF are each treated as fully correlated across all search channels.

The dominant systematic uncertainties depend on the mass of the diboson resonance being considered. In the mass range \(1.15 \text{ to } 1.6 \text{ TeV}\), background modeling uncertainties dominate: SM diboson background in the `\(l\)\(\ell\)` channel and \(Z(W) + \text{jets}\) background for the `\(l\)\(\ell\)q\(\bar{q}\)` channel. In the higher mass region, background modeling uncertainties in the `\(l\)\(\ell\)q\(\bar{q}\)` channel as well as the large-R jet energy scale uncertainty dominate.
Sensitivity to diboson resonances

Figure 5: Comparison of the expected limits for individual and combined decay channels in the EGM $W_0$ signal model.

Figure 6: Comparison of the expected limits for individual and combined decay channels in the graviton signal model.
Combining picture in ATLAS

- The single lepton channel has a comparable sensitivity in most of the range where the fully hadronic search takes place
  - Excellent agreement with the background only hypothesis. No excess is observed

- The two and three lepton channels have less sensitivity at high masses but no excesses are observed either
  - Local significance in WZ is reduced to 2.5 sigma (at the global level this is a very mild excess)
CMS results

- CMS has performed searches for diboson resonances in similar channels
  - arXiv:1405.3447 (semileptonic)
The future...

Diboson resonance searches

- Yield of signal increases by a factor of ~10 at 2 TeV for W'
- Yield of signal increases by a factor of ~20 at 2 TeV for gravitons

Great opportunities for BSM searches with diboson final states

Junjie Zhu's talk

PDF luminosity ratio

L (14 TeV) / L (8 TeV)
Exhaustive boson tagging studies from Run-1 (ATL-PERF-2015-03)

- Consider large space of grooming / tagging configurations
  - $O(500)$ configurations tested

- Step-1
  - Determination of grooming algorithm based on jet mass (bkg rejection for 68% signal eff)
  - Additional considerations
    - Pileup dependence

- Step-2
  - Single variable tagging
    - Analyzed $O(20)$ variables
    - Best variables appear to be “proneness” related variables
Improved tagging at Run-2 based on Run-1 experience

Based on the results obtained in Run-1

- Started with reduced set of grooming algorithms and substructure variables
- Run 2 tagger: anti-k_t trimmed jets with $R = 0.2$, $f_{cut} = 5\%$, $R_{sub} = 0.2$

Jet mass $[\text{GeV}]$

- Normalised to unity
- $0$ $20$ $40$ $60$ $80$ $100$ $120$ $140$ $160$ $180$ $200$

ATLAS Simulation Preliminary

- anti-k, $R = 1.0$ jets
- Trimmed ($f_{cut} = 5\%$, $R_{sub} = 0.2$)
- $|\eta^{Jub}| < 2.0$
- $p_T^J = 13 \text{ TeV}$

Jet p_T $[\text{GeV}]$

- Fitted mean + $\sigma$
- Linear fit

$D_2$ @ 50% signal eff.

- Fit: fourth order polynomial

Jet p_T $[\text{GeV}]$

- $500$ $1000$ $1500$ $2000$

ATLAS-PHYS-PUB-2015-033
Summary

- The large dataset collected in Run-1 of the LHC provided the exciting opportunity to explore new particles at the TeV scale decaying to W/Z's.

- The excellent spatial resolution of the calorimeters in the experiment(s) allowed to develop dedicated techniques to reconstruct boosted bosons decaying to hadrons.
  - This is just the beginning!

- There is tension with other searches:
  - In ATLAS the fully hadronic channel shows a not-significant-enough excess around 2 TeV. But... other channels of comparable sensitivity are in good agreement with background only predictions.
  - CMS has seen some mild excesses in the same general region in searches with comparable sensitivity in this region. But... at lower mass scale. The uncertainty in the Jet Energy Scale estimated by both experiments is smaller than the difference in the mass of the excesses.

- Run-2 is here! Data is beginning to flow quickly:
  - Massive cross section increase if the excess depending on production mechanism.
  - If all goes well $O(5fb^{-1})$... in Spring experiments could confirm / exclude the excess.
Thanks!
Backup
Systematic uncertainties

- In ATLAS systematic uncertainties follow the following approach
  - Two independent measurements for jet related quantities
    - Track based
    - Calo based
  - Compare ratio of Calo / Track in data to MC and use maximal deviation from unity to derive uncertainty
  - Check with different simulations

### Summary of the systematic uncertainties

<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_{p_T}</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>

<table>
<thead>
<tr>
<th>Source</th>
<th>Normalisation 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>
Kinematic effects?

(a) Single boson tagging requirement applied

(b) All tagging requirements except one applied
Mass window optimization

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

\( W'(1.8\ TeV) \rightarrow WZ \rightarrow qqqq \)

BDRS-A
| | 1.7 |
---|---|
| | 2.0 |
| | 0.15 |
| | 0.45 |
| | 30 |

min(\( m_1, m_2 \)) [GeV]

max(\( m_1, m_2 \)) [GeV]

JETS / 5 GeV

Nominal
JMS up
JMS down
JMR

For \( W'(1.8\ TeV) \)
\( |y| < 1.2 \)
\( |\eta| < 30 \)
\( A < 0.15 \)
\( \sqrt{y} > 0.45 \)

\( Z_{T_{Q}, T_{B}} \)
\( \sqrt{s} = 8\ TeV,\ 20.3\ fb^{-1} \)

\( Z_{T_{Q}, T_{B}} \)
\( \sqrt{s} = 8\ TeV,\ 20.3\ fb^{-1} \)

\( Z_{T_{Q}, T_{B}} \)
\( \sqrt{s} = 8\ TeV,\ 20.3\ fb^{-1} \)
Summary of the boson tagging selection

<table>
<thead>
<tr>
<th>Channel</th>
<th>Selection</th>
</tr>
</thead>
</table>
| $llqq$  | $70 < m_J < 110$ GeV  
$\sqrt{y} > 0.45$ |
| $lvqq$  | $65 < m_J < 105$ GeV  
$\sqrt{y} > 0.45$ |
| $JJ$    | $|m_J - m_\nu| < 13$ GeV  
$\sqrt{y} > 0.45$  
n_{trk} < 30 |

Due to the large backgrounds in the fully hadronic (JJ) channel a **tight** selection is necessary.

In the JJ channel different mass windows are used for W and Z. However, there is a considerable overlap between them (more on this later in the talk).
### Analyses summary - selection

<table>
<thead>
<tr>
<th>Channel</th>
<th>Leptons</th>
<th>Jets</th>
<th>$E_T^{\text{miss}}$</th>
<th>Boson Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\nu\ell'\ell'$</td>
<td>3 leptons $p_T &gt; 25$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 25$ GeV</td>
<td>$</td>
<td>m_{ll} - m_Z</td>
</tr>
<tr>
<td>$\ell\ell q\bar{q}$</td>
<td>2 leptons $p_T &gt; 25$ GeV</td>
<td>2 small-$R$ jets or 1 large-$R$ jet</td>
<td>$</td>
<td>m_{ll} - m_Z</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$70$ GeV $&lt; m_J &lt; 110$ GeV, $\sqrt{y} &gt; 0.45$</td>
</tr>
<tr>
<td>$\ell\nu q\bar{q}$</td>
<td>1 lepton $p_T &gt; 25$ GeV</td>
<td>2 small-$R$ jets or 1 large-$R$ jet</td>
<td>$E_T^{\text{miss}} &gt; 30$ GeV</td>
<td>$65$ GeV $&lt; m_{jj} &lt; 105$ GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No $b$-jet with $\Delta R(b, W/Z) &gt; 0.8$</td>
<td></td>
<td>$65$ GeV $&lt; m_J &lt; 105$ GeV, $\sqrt{y} &gt; 0.45$</td>
</tr>
<tr>
<td>$JJ$</td>
<td>0 lepton</td>
<td>2 large-$R$ jets, $</td>
<td>\eta</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sqrt{y} &gt; 0.45$, $n_{\text{trk}} &lt; 30$</td>
</tr>
</tbody>
</table>
## Analyses summary - regions

<table>
<thead>
<tr>
<th>Channel</th>
<th>High-(p_T) merged</th>
<th>High-(p_T) resolved (high mass)</th>
<th>Low-(p_T) resolved (low mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ell\ell'\ell')</td>
<td>–</td>
<td>(\Delta y(W, Z) &lt; 1.5)</td>
<td>(\Delta \phi(\ell^{3rd}, E_T^{miss}) &lt; 1.5)</td>
</tr>
<tr>
<td>(\ell\ell q\bar{q})</td>
<td>(p_T(\ell\ell) &gt; 400) GeV, (p_T(J) &gt; 400) GeV</td>
<td>(p_T(\ell\ell) &gt; 250) GeV, (p_T(jj) &gt; 250) GeV</td>
<td>(p_T(\ell\ell) &gt; 100) GeV, (p_T(jj) &gt; 100) GeV</td>
</tr>
<tr>
<td>(\ell\nu q\bar{q})</td>
<td>1 large-(R) jet, (p_T &gt; 400) GeV</td>
<td>2 small-(R) jets, (p_T &gt; 80) GeV</td>
<td>2 small-(R) jets, (p_T &gt; 30) GeV</td>
</tr>
<tr>
<td>(\ell\nu q\bar{q})</td>
<td>(p_T(\ell\nu) &gt; 400) GeV</td>
<td>(p_T(jj) &gt; 300) GeV, (p_T(\ell\nu) &gt; 300) GeV</td>
<td>(p_T(jj) &gt; 100) GeV, (p_T(\ell\nu) &gt; 100) GeV</td>
</tr>
<tr>
<td>(JJ)</td>
<td>(</td>
<td>\Delta y_{12}</td>
<td>&lt; 1.2)</td>
</tr>
<tr>
<td>(JJ)</td>
<td>(m(JJ) &gt; 1.05) TeV</td>
<td>(m(JJ) &gt; 1.05) TeV</td>
<td>(m(JJ) &gt; 1.05) TeV</td>
</tr>
</tbody>
</table>

\(\Delta \phi(E_T^{miss}, \bar{j}) > 1\) (electron channel)
\( \mu \) is the ML estimator for the common signal strength for the model in question. If the two channels being compared have a common signal strength, i.e. \( \mu = \mu_A = \mu_B \), then in the asymptotic limit \( 2 \log(\mu) \) is expected to be \( \chi^2 \)-distributed with two degrees of freedom.

In the combined analysis to search for \( W_0 \) resonances, all four individual channels are used. For the charge-neutral bulk \( G^* \), only the \( `⌫qq \), `\( q \bar{q} \)`, and the \( JJ \) channels contribute to the combination, and in the case of the fully hadronic channel, a merged signal region resulting from the union of the \( WW \) and \( ZZ \) signal regions is used in the analysis. The background to this merged signal region is estimated using the same technique as for the individual signal regions.

Table 4:
Channels and signal regions contributing to the combination for the EGM \( W_0 \) and bulk \( G^* \).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal Region</th>
<th>( W' ) mass range [TeV]</th>
<th>( G^* ) mass range [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \ell\ell'\ell' )</td>
<td>low-mass</td>
<td>0.2-1.9</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>high-mass</td>
<td>0.2-2.5</td>
<td>–</td>
</tr>
<tr>
<td>( \ell\ell q\bar{q} )</td>
<td>low-( p_T ) resolved</td>
<td>0.3-0.9</td>
<td>0.2-0.9</td>
</tr>
<tr>
<td></td>
<td>high-( p_T ) resolved</td>
<td>0.6-2.5</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td></td>
<td>merged</td>
<td>0.9-2.5</td>
<td>0.9-2.5</td>
</tr>
<tr>
<td>( \ell\nu q\bar{q} )</td>
<td>low-( p_T ) resolved</td>
<td>0.3-0.8</td>
<td>0.2-0.7</td>
</tr>
<tr>
<td></td>
<td>high-( p_T ) resolved</td>
<td>0.6-1.1</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td></td>
<td>merged</td>
<td>0.8-2.5</td>
<td>0.8-2.5</td>
</tr>
<tr>
<td>( JJ )</td>
<td>( WZ ) selection</td>
<td>1.3-2.5</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>( WW+ZZ ) selection</td>
<td>–</td>
<td>1.3-2.5</td>
</tr>
</tbody>
</table>

Fig. 2 shows the combined upper limit on the EGM \( W_0 \) production cross section times its branching ratio to \( WZ \) at the 95\% CL in the mass range from 300 GeV to 2.5 TeV. The observed limit is compared to the expected limit and the theoretical EGM \( W_0 \) prediction. The largest deviation from the background expectation is found at \( \sim 2 \) TeV with a local \( p_0 \)-value corresponding to 2.5 standard deviations. This is smaller than the \( p_0 \)-value of 3.4 observed in the \( JJ \) channel since the other channels are more consistent with the background-only hypothesis. In the context of the EGM \( W_0 \) benchmark, the results of the combined \( `⌫`0 `\( q \bar{q} \), and \( `⌫`q\bar{q} \) channels and the \( JJ \) channel are compared in the mass region around 2 TeV following the consistency test described in Section 7 and are found to be inconsistent at the level of 2.9. The resulting lower limit at the 95\% CL on the EGM \( W_0 \) mass, using a LO cross section calculation, after the full combination is observed to be 1.81 TeV, with an expected limit of 1.81 TeV. The most stringent observed mass limit of an individual analysis is 1.59 TeV at NNLO in the \( `⌫`q\bar{q} \) channel.

In Fig. 3 the observed and expected combined upper limit on the bulk \( G^* \) production cross section times its branching ratio to \( WW \) and \( ZZ \) at the 95\% CL is shown in the mass range from 200 GeV to 2.5 TeV, together with the theoretical bulk \( G^* \) prediction. In the context of the bulk \( G^* \) benchmark, the results of the combined \( `⌫`0 `\( q \bar{q} \), and \( `⌫`q\bar{q} \) channels and the \( JJ \) channel are compared in the mass region around 2 TeV following the consistency test described in Section 7 and are found to be inconsistent at the level of 17th September 2015.
ATLAS detector

Figure 180: ATLAS detector layout.

Figure 181: Muon spectrometer layout.

Figure 182: Interaction length for the ATLAS Electromagnetic calorimeter (top) and for the full ATLAS detector (bottom) as a function of $|\eta|$. 

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ATLAS tile calo sectioning
$\sigma_{pp \rightarrow G^*} \times BR(G^* \rightarrow WW)$ [pb]

**ATLAS Preliminary**

$\sqrt{s} = 8$ TeV

$\int L \, dt = 20.3$ fb$^{-1}$

- **Bulk RS graviton $k/M_{Pl} = 1$, Leading Order**
- **Expected 95% CL**
- **Observed 95% CL**

± 1σ uncertainty
± 2σ uncertainty

Channels Combined: $l\nu qq + JJ$
$\sqrt{s} = 8 \text{ TeV} \\
\int L \, dt = 20.3 \text{ fb}^{-1}$

**ATLAS Preliminary**

- **Bulk RS graviton $k/M_{Pl} = 1$, Leading Order**
- **Expected 95% CL**
- **Observed 95% CL**
- **$\pm 1 \sigma$ uncertainty**
- **$\pm 2 \sigma$ uncertainty**

Channels Combined: $llqq + JJ$