Searches for new physics in diboson resonances and other signatures with the ATLAS detector at the LHC

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   \[ WV \rightarrow l\nu jj/l\nu J \]
   \[ WZ \rightarrow l\nu ll \]
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   \[ H^\pm \rightarrow W^\pm Z \]
   \[ VH \rightarrow \nu\nu/l\nu/ll + b\bar{b} \]
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   \[ VG \rightarrow l\nu/ll + \gamma \]
   \[ ZV \rightarrow lljj/llJ \]
Physical Models Relevant to this Talk

- **Randal-Sundrum Based Model (RS I):** Predicting an extra compactified dimension, we search the lowest graviton mode, $G^*$.
- **Extended Gauge Model (EGM):** Predicting heavier versions of the $W$ and $Z$ bosons, the $W'$ and $Z'$.
- **Hidden Valley:** Predicting a hidden sector connected to the SM through *communicators*, the predicted particles are a scalar $\phi$, a $Z'$ and a triplet $\pi_V^\pm, \pi_V^0$.
- **Stealth SUSY:** Low scale, R-parity conserving SUSY, predicting a long lived particle, $\tilde{S}$ with almost the same mass as its superpartner, $S$.
- **Minimal Walking Technicolor (MWT):** Particular version of Technicolor, predicts the existence of $R_{1,2}^\pm$ and $R_{1,2}^0$.
- **Low Scale Technicolor (LSCT):** Particular version of Technicolor, predicts the existence of $a_T, \omega_T$ and $\phi_T$.
- **Type III Seesaw:** Predicting a triplet $\Sigma^\pm, \Sigma^0$.
- **Heavy Vector Triplet (HVT):** Based on a phenomenological Lagrangian, the resonances searched are $V^\pm$ and $V^0$.
- **Georgi-Machacek Higgs Triplet Model (GMHTM):** Predicts the existence of charged higgs bosons $H^\pm$. 
Motivation

Diboson Searches

Summary

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Physical Models Relevant to this Talk

ATLAS data coming from $\sqrt{s} = 8$ TeV $pp$ collisions is used to search for narrow diboson resonances and other predicted particles.

Randal Sundrum I model.

Extended Gauge Model.

Hidden Valley.

GMHTM.

Stealth SUSY.

Type III Seesaw.
Hadronic Boson Reconstruction

Different clustering algorithms can be used for reconstructing the jets originating from a vector boson decay, depending on the boson $p_T$.

**Hadronically Decaying Bosons**

If the $p_T$ of the bosons is low enough the two quarks in which they decay will hadronize in two well separated jets, this is the **resolved regime**.

**LRR:** If for both bosons $p_T > 100\text{GeV}$.

**HRR:** If for both bosons $p_T > 250(300)\text{GeV}$ for ZV(WV) analysis.

If the $p_T$ of the bosons is large enough the quarks from its decay will form a **single fat** jet, this is the **merged regime**.

**MR:** Merged regime, if for both bosons $p_T > 400\text{GeV}$. Enables the use of a split filtering algorithm optimized for high $p_T$ jets, this algorithm is described in slide 32.

In order to reconstruct Higgs bosons b-jets are identified with a neural network based algorithm that achieves 70% efficiency.
Leptonic Boson Reconstruction

The analyses reviewed here follow roughly the requirements listed below when dealing with leptons.

Leptonically Decaying Bosons

- The leptons are required to pass isolation requirements in the Inner Detector and in the Calorimeter.
- The leptons are required to be isolated $\Rightarrow$ for boosted Z bosons decaying into two leptons $l_1$ and $l_2$, $\Delta R(l_1, l_2)$ is very small and many events fail isolation $\Rightarrow$ energy of $l_2$ has to be ignored when applying isolation requirements to $l_1$ and vice versa, this is an optimized isolation algorithm for boosted bosons.
- The lowest $p_T$ of the electrons and muons should be above $\approx 25$ GeV.
- Electrons most of the time are required to be in $|\eta| < 2.7$ excluding $1.05 < |\eta| < 2.4$, the precision region of the Electromagnetic Calorimeter.
- Neutrinos $p_T$'s are taken as the $p_T^{\text{miss}}$ in the event and their $p_z$ are obtained by requiring $M_W = M_{l\nu}$. 
Diboson Searches
**Event Selection**

- Analysis triggers on events with one electron or one muon.
- It uses merged and resolved regimes to reconstruct hadronic bosons which should lie in $65 < m_{jj}/j < 105\text{GeV}$.
- $E_T^{\text{miss}} > 30\text{GeV}$.

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Background Estimation and Limits

- The main background comes from W/Z+jets events
- This background is estimated with simulated samples corrected with data using control regions.
- For the control regions, the mass of the boson is restricted to the sidebands $40 < m_{jj} < 65\text{GeV}$ and $105 < m_{jj} < 200\text{GeV}$ of the LRR.

Upper limits on the $\sigma \cdot BR$ for a RS I graviton and an EGM $W'$, combining merged and resolved regimes.
Motivation

**Event Selection**

- Exactly three leptons are required with a $p_T > 25$ GeV.
- Two signal regions are defined, one for high mass signals ($S_{HM}$) with $\Delta\phi(l, E_T^{miss}) < 1.5$ and another for low mass signals $S_{LM}$ with $\Delta\phi(l, E_T^{miss}) > 1.5$.

**ATLAS**

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

**SR_{LM}: All channels combined**

**SR_{HM}: All channels combined**

![Graph showing data, WZ, ZZ, W/Z, t\bar{t}, other background, W'(200 GeV), and W'(600 GeV), W'(1000 GeV), W'(1400 GeV) samples.]
**Background Estimation and Limits**

- The background is dominated by WZ/ZZ and $t\bar{t} + W/Z$ events.
- The simulation modeling of these backgrounds is validated on a control region consisting of the $\Delta y(W, Z)$ cut reversed and the $\Delta\phi(l, E_T^{miss})$ dropped.

At the left the upper observed limits on the $\sigma \cdot BR$ for an EGM $W'$, combining low and high signal regions. At the right the exclusion contours in the HVT parameter space.
**Motivation**

**Diboson Searches Summary**

**Backup**

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**VV → JJ, Preliminary**

### Event Selection

- Analysis triggers on events with a large-R jet with $p_T > 360\text{GeV}$.
- The analysis uses only the merged regime (due to the high $p_T$ of the bosons) and substructure quantities are used to tag the bosons.
- The bosons are required to be within 13GeV from the mass of the W or Z, other cuts are applied on the jet’s number of tracks, $\Delta y(J_1, J_2)$...

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**ATLAS Preliminary**

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

**WZ Selection**

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

**WW Selection**

- Data
- Background model
- Significance (stat)
- Significance (stat + syst)
Background Estimation and Limits

- The background is dominated by SM QCD dijet events with small contribution from $W/Z + jets$.
- The background is estimated by fitting the data, the systematics on the background come from the error in the fitting parameters.
Event Selection

- The $W$ boson, reconstructed from the highest $p_T$ central ($|\eta| < 2.5$) jets, has to be in $60 < m_{jj} < 95\text{GeV}$.
- The $Z$ boson, reconstructed from two leptons required to be oppositely charged, has to be in $83 < m_{ll} < 99\text{GeV}$.
Background Estimation and Limits

- The shapes of all the backgrounds are estimated from simulation, except the multijet background that is taken from data.
- The $Z + jets$ background normalization is left as a free parameter in the fit to the data.
- The largest systematic uncertainties come from the $Z + jets$ normalization and modeling.

At the right the upper limits on $\sigma \cdot BR$ for a $H^\pm$, at the right the same upper limits for the model parameter $S_H$. 

**Motivation**

**Diboson Searches Summary**

**Backup**

\[ VH \rightarrow \nu\nu/\ell\nu/\ell\ell + b\bar{b}, \]


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**Event Selection**

- The data is split into samples with 1 b-tagged jet and 2 b-tagged jets. AntiKt 0.4 jets are used.
- The Data is also split in three categories, events with zero, one and two leptons.
- A cut on the \( p_T \) of the boson as a function of the reconstructed mass was used.

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![Graphs showing event selection for different categories](image-url)
**Background Estimation and Limits**

- All backgrounds except the multijet background are taken from simulation corrected with data in control regions.
- The $W/Z + jets$ and $t\bar{t}$ modeling are the dominant sources of systematics; they are obtained comparing different generators and by looking at any residual discrepancy in the control regions.

Limits on $R_{1}^{(\pm, 0)}$ (Minimal Walking Technicolor) and $V^{(0, \pm)}$ (Heavy Vector Triplet).
**Motivation**

**Diboson Searches**

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**HH → b(bb)b, Preliminary**

### Event Selection

**Merged Regime:** Select events with two large-R jets, build from their tracks AntiKt jets with $R = 1.0$ and trim them, using $\Delta R = 0.3$ subjets to get rid of QCD, find b-jets among the subjets.

**Resolved Regime:** Select events with at least 4 b-tagged jets and form dijets with highest $p_T$ jets, then apply mass dependent cuts.

The same b-tagging algorithm is used in both regimes.

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**Resolved Regime**

**Boosted Regime**
Background Estimation and Limits

- The background is dominated by multijet (95%) and $t\bar{t}$ (5%) events.
- The multijet background is modeled using data and the $t\bar{t}$ background uses simulation for the shape, the normalization is deduced using data.
- Boosted and resolved regimes are combined to achieve the highest sensitivity.

Upper Limits on $\sigma \cdot BR$ after combining the merged and resolved regime for the a Graviton (left) and a Heavy Higgs (right).
• Several searches have been reviewed in diboson channels and other channels, they use the full 2012 ATLAS dataset of $pp$ collisions at $\sqrt{s} = 8$TeV.

• No new physics has been found so far but excess at 2TeV was found in the $VV \rightarrow JJ$ analysis with a global significance of $2.5\sigma$. 
BACKUP
Event Selection

Two models are used, Stealth SUSY and Hidden Valley, they predict long lived resonances giving rise to displaced vertices. Below are the Feynman diagrams corresponding to these processes. **The blue lines represent long lived particles.**

**Trigger:** A displaced vertex can be in the ID the MS or outside the detector, so there are two analyses. One triggers on events with a jet and $E_T^{\text{miss}}$, the case of a Hidden Valley $Z'$. In the other analysis one triggers on events with a displaced vertex in the MS, the case of Stealth SUSY or a scalar boson.
Physics Objects and Event Selection

- Analysis tries to isolate true displaced vertices from fake ones.
- For the jet + $E_T^{\text{miss}}$ analysis the jet is required to have an $E_T > 110\text{GeV}$ and $E_T^{\text{miss}} > 75\text{GeV}$.
- For real displaced vertices in the ID the number of tracks is smaller than for displaced vertices reconstructed randomly and vertices from hits on material. To deal with these hits also a cut on the distance to the closest ID layer is applied.
- For vertices in the MS a cut on the number of tracks is also applied to deal with leaked jets from the HCal and with random noise.

Below are the reconstruction efficiencies for a displaced vertex in the Barrel and End-Cap for different signals.
Limits

Below are the plots of the observed upper limits for three different signals, the first two correspond respectively to a scalar $\phi$ and a $Z'$ belonging to the Hidden Valley model, the third one refers to a singlino $\tilde{S}$, the superpartner of the singlet $S$. 

![Plot of observed upper limits for scalar $\phi$](image1)

![Plot of observed upper limits for $Z'$](image2)

![Plot of observed upper limits for singlino $\tilde{S}$](image3)
Event Selection

- The process sought is $pp \rightarrow W^* \rightarrow \Sigma^0 \Sigma^\pm$ where $\Sigma^0 \rightarrow W^\pm l^\mp$ and $\Sigma^\pm \rightarrow W^\pm \nu$. One of the $W$'s decays to two jets and the other decays leptonically, therefore the final state contains 2 leptons and two jets.

- The data set is divided into final states with same sign (SS) and opposite sign (OS) leptons.
Event Selection

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Type III Seesaw, **Preliminary**

**Limits**

Below are shown the limits on $\sigma \cdot BR$ for the cases in which $\Sigma^0$ couples to both electrons and muons, only electrons or only muons.
$V\gamma \rightarrow l\nu/l\ell + \gamma,$  [Link to arXiv paper](http://arxiv.org/pdf/1407.8150v2.pdf)

**Event Selection**

- The Z boson is reconstructed from leptons in $65 < m_{ll} < 115\text{GeV}$.
- The transverse mass of the reconstructed W has to satisfy $M_W > 40\text{GeV}$.
Background Estimation and Limits

The background is made mostly of SM $W/Z + \gamma$, $W/Z + \text{jets}$, $\gamma + \text{jets}$, $t\bar{t}$, and it is calculated by fitting a sum of two exponentials to the data.

Observed upper limits on $\sigma \cdot BR$ for $a_T$ and $\omega_T$ in function of their masses.

**Event Selection**

- The analysis triggers on events with one electron or one muon.
- It uses merged and resolved regimes to reconstruct hadronic bosons which should lie in $70 < m_{jj/J} < 110\text{GeV}$.
- Makes use of an **optimized isolation** cut for boosted Z’s to reconstruct Z bosons which should lie in $66 < m_{ll} < 116\text{GeV}$.
**Background Estimation and Limits**

- The main background is Z+jets events.
- This background is estimated with simulated samples corrected using data in the control region.
- The control regions is taken as either $m_{jj/J} < 70\text{GeV}$ or $m_{jj/J} > 110\text{GeV}$.

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Upper limits on the $\sigma \cdot BR$ for a bulk RS graviton and an EGM $W'$, combining merged and resolved regimes.
# Filtering C/A jets

A split-filtering algorithm is used in WV, ZV and VV channels to clean C/A 1.2 jets from QCD contamination.

## Filtered Jets

C/A 1.2 jets are made of calorimeter clusters. To get rid of QCD contamination, decluster C/A jets and keep pair if $y_f > y_{f_{\text{min}}}$, otherwise keep only hardest jet (groom). Repeat until a pair is found or until nothing is left, then recluster what is left with C/A $R_{\text{filt}}$ and keep the 3 leading subjets.

\[
y_f = \frac{\min(p_{T1}^2, p_{T2}^2)}{m_0^2} \Delta R_{12}^2 \approx \frac{\min(p_{T1}, p_{T2})}{\max(p_{T1}, p_{T2})}
\]

(1)

\[
\mu_f = \frac{\max(m_1, m_2)}{m_0}
\]

(2)

## Splitting and Grooming

\[
m_{h/M_{\text{jet}}} < \mu_{\text{frac}} \quad \text{and} \quad y > y_{\text{cut}}
\]

## Reclustering and Filtering

The algorithm attempts to catch each boson in a single C/A 1.2 jet and remove the QCD contamination.
Merged and Resolved Regime Efficiencies

Acceptance times efficiency for many signal hypothesis in the $WV$ channel (upper) and the $ZV$ channel (below) for merged and resolved regimes.
Merged and Resolved Regime Efficiencies

Acceptance times efficiency for different signal hypotheses for the $HH \to b\bar{b}b\bar{b}$.
All the searches listed here use the full 2012 ATLAS dataset. $l$ stands for lepton and all the analyses presented here using leptons use electrons and muons.

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<th>Jets</th>
<th>Background</th>
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<td>AntiKt-0.4 C/A-1.2</td>
<td>MC+Data</td>
<td>link</td>
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<tr>
<td>$ZV \rightarrow lljj/J$</td>
<td>$W', G^*$</td>
<td>AntiKt-0.4 C/A-1.2</td>
<td>MC+Data</td>
<td>link</td>
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<tr>
<td>$VV \rightarrow JJ$</td>
<td>$W', G^*$</td>
<td>C/A 1.2</td>
<td>Data</td>
<td>preliminary</td>
</tr>
<tr>
<td>$WZ \rightarrow l\nu ll$</td>
<td>$W', V^0, V^\pm$</td>
<td>–</td>
<td>MC+Data</td>
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</tr>
<tr>
<td>$VH \rightarrow ll/ll$</td>
<td>$R_{1,2}^0, R_{1,2}^\pm$</td>
<td>AntiKt-0.4</td>
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</tr>
<tr>
<td>$/\nu\nu + bb$</td>
<td>$V^0, V^\pm$</td>
<td>AntiKt-0.4</td>
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<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>$G^*, H$</td>
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<tr>
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<td>Long Lived</td>
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