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

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On behalf of the ATLAS Collaboration
Diboson resonances

- Resonant production of two massive bosons (WW, WZ, ZZ and HH) is a smoking gun signature for physics beyond the Standard Model. Just selected examples:
  - Grand Unified Theories
  - Warped extra dimensions
  - Technicolor

- From experimental point of view:
  - Clear signature
  - Need to develop novel techniques to handle boosted topologies from high-mass resonances
Run1 Analyses in ATLAS

- **Analyses presented here**
  
  - VV → qq qq \text{ arXiv:1506.00962}
  - HH → bbbb \text{ arXiv:1506.00285}

- **Further diboson resonance searches in ATLAS (not shown here):**
  
  - Heavy H → γγ/ZZ \text{ arXiv:1507.05930 (see talk by Graham Cree for more details)}
  - HH → γγbb \text{ Phys. Rev. Lett. 144, 081802}
  - Wγ/Zγ → lνγ/llγ \text{ PLB 738 (2014) 428-447}
Strategy for diboson resonance searches

- How to search for diboson resonances
  - Observable: *invariant mass of diboson system* $m_{VV}$
  - Search for narrow resonance on top of smoothly falling background distribution
  - Limits set on benchmark models

- Decay modes:
  - *Fully leptonic*
    - Low background
    - High purity
    - Low branching fraction
  - *Semileptonic*
  - *Fully hadronic*
    - Large branching ratio
    - No MET
    - Large background

- Higgs boson as a *tool* for searches of new physics

- Develop novel techniques to cope with *boosted topologies* of final states

### Observable:

- $W$:
  - $M \sim 80.3$ GeV
  - $W \rightarrow qq' \sim 67\%$
  - $W \rightarrow lv \sim 33\%$

- $Z$:
  - $M \sim 91.2$ GeV
  - $Z \rightarrow qq \sim 70\%$
  - $Z \rightarrow vv \sim 20\%$
  - $Z \rightarrow ll \sim 10\%$

- $H$:
  - $M \sim 125$ GeV
  - $H \rightarrow bb \sim 57\%$
  - $H \rightarrow ZZ \sim 3\%$
  - $H \rightarrow ll \sim 6\%$
  - $H \rightarrow \gamma\gamma \sim 0.2\%$
Benchmark models

Main models used as benchmark in Run1 analysis:

- **Extended Gauge Model (EGM)**
  - Sequential Standard Model (modified WZ coupling)
  - Spin-1 gauge boson ($W'$)
  - qqbar production
  - Decay in WZ
  - For $m_{W'} = 1$ TeV: $\text{BR}(W' \rightarrow WZ) \sim 1.3\%$

- **Bulk Randall-Sundrum model**
  - Model of warped extra dimensions
  - Spin-2 Kaluza-Klein graviton ($G^*$)
  - Gluon-gluon production
  - Decays into $WW, ZZ$
  - $m_{G^*} = 1$ TeV:
    - $\text{BR}(G^* \rightarrow WW) \approx 20\%$
    - $\text{BR}(G^* \rightarrow ZZ) \approx 10\%$

- **Minimal walking technicolor**
  - Technicolor with minimal ingredients, can decay to $ZH$ and $WH$

- **Heavy Vector Triplet (HVT)**
  - A simplified Lagrangian can be used, limits derived on $\sigma \times \text{BR}$ can then be translated into any specific model
ATLAS and LHC

Run Number: 190300
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET

EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <4cm
Rphi <4cm

Muons: blue
Cells: tiles, EMC

Persint
Dilepton Isolation

- Leptons from highly boosted boson decay can approach each other, compromising the isolation criteria used for candidate identification

- **Standard isolation**
  - \( p_{\text{cone}20} < 0.15 \ p_{T}^{l_1} \)

- **Dilepton isolation**
  - If \( \Delta R(l_1, l_2) < 0.25 \):
    - \( p_{\text{cone}20} - p_{T}^{l_2} < 0.15 \ p_{T}^{l_1} \)
  - else:
    - standard isolation

![ATLAS Simulation](image-url)
Boosted boson jets

- For resonance masses above O(1 TeV) the vector-boson decay products are **boosted**
  → reconstruction as **one single large-radius jet**

- **Grooming techniques**
  - Clean the large-R jet from soft gluon radiation and pile-up effects that diminish jet mass resolution
  - Techniques: BDRS (mass-drop/filtering), trimming, pruning

- **Substructure information (tagging)**
  - Use hard substructure of jet (not present in e.g. gluon jet) to improve background rejection
Boosted boson tagging

- **Jet reconstruction**:  
  - VV diboson searches presented here use C/A R = 1.2 jets groomed with the BDRS (split-filtering) algorithm

- **Splitting**:  
  - Require symmetric splitting  
    \[ \sqrt{y_f} = \frac{\min(p_{T1}, p_{T2})}{m_{12}} \times \Delta R_{12} \]  
  - No mass drop-criterion is used in ATLAS (\(\mu = 100\%\))  
  - Slightly modified version of BDRS using a fixed reclustering distance parameter

- **Filtering**: remove soft radiation
Boosted boson tagging

- **Boson tagging**:
  - VV diboson searches presented here use as tagging variable
    - the large-R jet mass $m_J$ (mass window around boson)
    - $y_J$ as tagging variable: $\sqrt{y_J} > 0.45$
  - QCD dijet events have unbalanced subjet momenta compared to signal jets due to soft gluon radiation
$WZ \rightarrow l\nu l\nu$

- Low background
- High purity
- Low branching fraction
- Neutrino in final state

Analysis strategy:
- 3 leptons (e, $\mu$);
- $Z$ reconstructed from same flavour leptons;
- Dilepton isolation applied;
- $W$ reconstructed using $m_W$ mass constraint
- Search for a bump in $m_{WZ}$ spectrum

*Exclude $M(W') < 1.52$ TeV*
$Z \rightarrow llq\bar{q}$

- $Z \rightarrow ll$
  - 2 isolated, same flavour leptons, compatible with $Z$ mass;
  - For $p_T^{Z} > 800$ GeV Dilepton isolation applied;

- $V \rightarrow qq$
  - 3 regions (LR, HR, MR);
  - In Merged region: one Large-R C/A jet + using substructure to improve sensitivity (optimized for longitudinally polarized vector-bosons)

\[
70 \text{GeV} < m_{J} < 110 \text{GeV}, \sqrt{y_f} > 0.45
\]

- *Low-pT resolved region (LR)*
  - $p_T^{ll} > 100$ GeV
  - $p_T^{l\bar{l}} > 100$ GeV ; $70 \text{GeV} < m_{jj} < 110 \text{GeV}$

- *High-pT resolved region (HR)*
  - $p_T^{ll} > 250$ GeV
  - $p_T^{l\bar{l}} > 250$ GeV ; $70 \text{GeV} < m_{jj} < 110 \text{GeV}$

- *Merged region (MR)*
  - $p_T^{ll} > 400$ GeV
  - $p_T^{l\bar{l}} > 400$ GeV ; $70 \text{GeV} < m_{J} < 110 \text{GeV}$
ZV $\rightarrow llqq$

- Dominant background: Z+jets
  - Normalization and shape correction for $m_J$ determined in data using control regions ($m_J < 70$ GeV or $m_J > 110$ GeV)
- Dominating systematic uncertainties: normalization and shape uncertainties from Z+jets background (11% – 47%)

Exclude $M(G^*) < 740$ GeV and $M(W') < 1590$ GeV
WV → lvqq

- Exactly one lepton
- $E_{T\text{miss}} > 30$ GeV
- Signal region divided in 3 orthogonal selection region

**Low-pT resolved region (LRR)**
- $p_{T_{lv}} > 100$ GeV ; $p_{T_{jj}} > 100$ GeV
- $\Delta\phi(j, E_{T\text{miss}}) > 1$

**High-pT resolved region (HRR)**
- $p_{T_{lv}} > 300$ GeV ; $p_{T_{jj}} > 300$ GeV
- $\Delta\phi(j, E_{T\text{miss}}) > 1$ ; $p_{T_{j}} > 80$ GeV

**Merged region (MR)**
- $p_{T_{lv}} > 400$ GeV ; $p_{T_{j}} > 400$ GeV
- $\Delta\phi(J, E_{T\text{miss}}) > 1$ ; $60$ GeV < $m_j$ < $105$ GeV
**WV \rightarrow l\nu qq**

- **Main backgrounds:**
  - MC: W/Z+jets, ttbar
  - Data driven: Multijet QCD \rightarrow loosened lepton selection to extract template and fit to the $E_{T}^{\text{miss}}$ to extract normalization

- Maximum likelihood fits to $m_{\nu J}$ distribution taking systematic uncertainties into accounts as nuisance parameters

**Exclude $M(G^*) < 760$ GeV and $M(W') < 1490$ GeV**
**Event Selection**
- Fully hadronic final state
- Only boosted regime is considered
- Reject events with electron or muon candidate or $E_{T}^{\text{miss}} > 350$ GeV (orthogonal to other diboson resonance searches)
- Rapidity difference: $|y_1 - y_2| < 1.2$
- $p_T$ asymmetry: $|(p_{T1} - p_{T2})|/(p_{T1} + p_{T2}) < 0.15$
- $m_{JJ} > 1.05$ TeV: trigger plateau of large-$R$ jet trigger

**Boson tagging**
- Jet mass (26 GeV window around $m_V$)
- $\sqrt{y_f} > 0.45$
- Number of charged-particle tracks associated to the ungroomed jet: $n_{\text{trk}} < 30$: expect QCD jet to be composed of more hadrons
- Efficiency is measured in data

**Overlap between $WW$, $WZ$, $ZZ$ selection due to chosen mass window**
Background invariant dijet mass spectrum assumed to be described by a smoothly falling distribution:

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

- Maximum-likelihood fit performed to data to estimate background
- Good agreement between data and background model over full dijet mass range except for region around \(m_{JJ} = 2\) TeV
- Frequentist approach used to interpret data:
  - **Local significance:**
    - WZ : 3.4\(\sigma\), WW : 2.6\(\sigma\), ZZ : 2.9\(\sigma\)
  - **Global significance:**
    - WZ : 2.5\(\sigma\)
- The 3 regions cannot be directly combined since they are not statistically independent
• Limits are calculated through profile likelihood
• Cross-section times branching ratio for bulk graviton production with chosen model parameters too low to be excluded

**Exclude 1300 GeV < M(W') < 1500 GeV**
VH→ll/lν/νν+bb

- Events are categorized according to:
  - Number of charged leptons
  - Number of b-tags
  - Run1 VH search uses **resolved channels only**

- Background estimation:
  - W/Z+j (dominant background); simulation with data-based corrections
  - Multi-jet background; data driven
  - tt/single top; normalized using control region fit
VH→ll/lv/vv+bb

- Benchmark models:
  - Minimal Walking Technicolor (MWT);
  - Heavy Vector Triplet (HVT)

- The experimental limits are obtained using samples with a single resonance $R_1$; however, the theory curve line for MWT includes both $R_1$ and $R_2$. The dip near 500 GeV in this theory curve is due to the interference between $R_1$ and $R_2$. 

![Graphs showing experimental and theoretical results](image-url)
HH→bbbb

- **Resolved analysis**
  - 4 b-jets
  - 2 dijets with $M_{jj} \sim M_H$
  - ttbar veto

- **Boosted analysis**
  - Select events with two “H → bb”-tagged large-R jets

- **H → bb tagging**
  - Trimmed Anti-$k_t$, R=1.0 jets with mass cut
  - 2 b-tagged Anti-$k_t$, R=0.3 track-jets
  - Improved efficiency in finding Higgs jets
  - Effective suppression of QCD

Graphs and equations are not included in the text but are referenced in the image.
• Multijet background (from data)
  - 2-btag → 4-btag extrapolation
  - Validation in signal-depleted sidebands
For the resonant Higgs boson pair production search, the resolved and boosted analyses offer their best sensitivity in complementary resonance mass regions.

In the combination, for each of the signal models, the limit for each mass point is taken from the analysis which offers the most stringent expected exclusion.

Limits are evaluated for several configuration of the parameters of the benchmark models.
Conclusions

- Diboson final states are a powerful tool in the search for New Physics at the TeV scale

Lesson from ATLAS in LHC Run1:
- Wide program of diboson searches
- Mature techniques to handle boosted topologies

What to expect for LHC Run2
- More energy
- More Luminosity
- More surprises ??
- More fun !!
Heavy Vector Triplet

- Two benchmark models
  - Model A → weakly coupled vector resonances from extension of the gauge group
  - Model B → HVT are produced in a strong scenario e.g. composite higgs model

- Couples to fermions through $c_F \left( \frac{g^2}{g_V} \right)$
- Couples to bosons through $c_H g_V$
  - $g$ is the SU(2) L gauge coupling
  - $g_V$ represents the coupling strength to vector bosons
  - $c_F$ and $c_H$ modify the couplings, and are close to unity in most models
Dilepton Isolation - muons

- Leptons from highly boosted boson decay can approach each other, compromising the isolation criteria used for candidate identification

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**Dilepton isolation**
- If \( \Delta R(l_1, l_2) < 0.25 \):
  - \( p_{T\text{cone20}} - p_{T2} < 0.15 \, p_{T1} \)
- else:
  - standard isolation
ZV → llqq – Merged Region

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)
\[ ZV \rightarrow llqq \]

**Low-pT resolved region (LR)**
- \( p_T^{ll} < 100 \text{ GeV} \)
- \( p_T^{ll} < 100 \text{ GeV} \); \( 70 \text{ GeV} < m_{jj} < 110 \text{ GeV} \)

**High-pT resolved region (HR)**
- \( p_T^{ll} < 250 \text{ GeV} \)
- \( p_T^{ll} < 250 \text{ GeV} \); \( 70 \text{ GeV} < m_{jj} < 110 \text{ GeV} \)

**Merged region (MR)**
- \( p_T^{ll} < 400 \text{ GeV} \)
- \( p_T^{ll} < 400 \text{ GeV} \); \( 70 \text{ GeV} < m_{jj} < 110 \text{ GeV} \)
\[ W \rightarrow \ell vq \]
$V V \rightarrow q q q q$
VV→qqqq
HH → bbbb
HH → bbbb
HH → bbbb