Searches for new physics with bosons at the ATLAS detector in LHC Run II

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Lake Louise Winter Institute 2016
INTRODUCTION

- Resonant production of two massive bosons
  
  Run I and Run II results

- Diphoton resonance production
  
  Run II results
Diboson Resonance Searches
Diboson resonances are predicted in a number of proposed extensions to the SM.

Benchmark models:
- Bulk RS graviton – Run I & II
- Extended Gauge Model (EGM) – Run I
- Heavy Vector Triplet (HVT) Model A – Run II

Parameters in the models are different to those used in the $V'/G_{RS} \rightarrow ll, qq$ analyses.

- Technicolor
- Warped extra dimensions
- Two Higgs doublet model (2HDM)
- Grand Unified Theories (GUTs)
- Sequential Standard Model (SSM)
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Mass $\sim$ TeV
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Hadronic jets are too close to each other to be resolved
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Define a large-R jet to encompass both jets

Trimming and boson tagging applied to large-R jets
Most interesting result comes from the $qqqq$ analysis. Local (global) significance of 3.4 $\sigma$ (2.5 $\sigma$) at 2 TeV.

The local significance at 2 TeV reduces to 2.5 $\sigma$ in the combination

EGM $W'$ excluded below 1.81 TeV
Bulk RS graviton excluded below 810 GeV
Several final states probed
Share object definitions and tools
Search for resonances in the range
700 GeV to 3000 GeV

Benchmark Models
Bulk RS graviton
Heavy Vector Triplet (HVT)

Parameters are chosen such as to resemble the
Run I EGM benchmark

Veto placed on $qq$ systems
to remove $b$-tagged jets.

<table>
<thead>
<tr>
<th>$VV$</th>
<th>$ZV$</th>
<th>$WV$</th>
<th>$ZH$</th>
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<tbody>
<tr>
<td>$\rightarrow q\bar{q}(\gamma)q\bar{q}(\gamma)$</td>
<td>$\rightarrow \nu\nu q\bar{q}(\gamma)$</td>
<td>$\rightarrow l\nu q\bar{q}(\gamma)$</td>
<td>$\rightarrow ll q\bar{q}(\gamma)$</td>
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Events / 100 GeV

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
Three (overlapping) signal regions are defined by placing cuts on the jet masses. Background modelled with a smoothly falling distribution.

**Selection Criteria**

- No charged leptons
- 2 large-R jets
- $p_T^{J1} > 450$ GeV
- $p_T^{J2} > 200$ GeV
- $|m_V - m_J| < 15$ GeV
- Reject jets in the range $110$ GeV < $m_J$ < $140$ GeV
- $E_T^{miss} < 250$ GeV

QCD multijet background dominates. Dominant uncertainties relate to large-R jet mass and energy measurement.

No significant excesses are observed.
DIBOSON \[ VV \rightarrow qqqq \]

Mass limits set for \( 1.2 \text{ TeV} < m_{JJ} < 2.2 \text{ TeV} \)

\( W' \) is excluded in the range \( 1.38 \text{ TeV} < m_{W'} < 1.60 \text{ TeV} \)

At 2 TeV, the Run I \( qqqq \) analysis was sensitive to cross-sections a factor of 3 smaller.

At this point there is no tension between the results.
**Selection Criteria**
- Exactly two same flavor leptons
- Muons are required to have opposite charge
- $p_T^\mu, E_T^e > 25$ GeV
- $p_T^J > 200$ GeV
- $83$ GeV $< m_{ee} < 99$ GeV
- $66$ GeV $< m_{\mu\mu} < 116$ GeV
- $p_T^{ll} > 0.4 m_{ll}$
- $p_T^J > 0.4 m_{ll}$

Dominant uncertainties relate to large-R jet mass and energy measurement.

A good agreement is seen between background only prediction and data.

The $vvqq$ and $lvqq$ analyses aren’t described in detail, but follow a similar strategy.

Background is dominated by $Z$+jets.

This background is estimated through a combination of MC and data-driven methods.
$W'$ excluded below 1400 GeV

$G_{RS}$ excluded below 850 GeV

Comparable sensitivities are present in the $vvqq$ and $lvqq$ analyses.

Heavy Higgs model also tested. Not optimized for this signal.
The background is dominated by $V$+jets. Dominant uncertainties relate to large-R jet mass and energy measurement.

The large-R jet is required to have either one or two b-tagged jets associated to it.

A good agreement is seen between background only prediction and data.
Limits are set independently on the 0, 1 and 2 lepton channels. Two HVT models are tested: Model A and B. Mass exclusions are given for the same model used in the previously described analyses.

- **Z’** is excluded below 1450 GeV
- **W’** is excluded below 1520 GeV
- **Z’** is excluded below 980 GeV

Heavy CP-odd scalar $A$, is also tested.
Summary

Cross section limits range from 700 GeV to 3 TeV.

Diboson analyses performed in a large range of final states.

Best mass limit exclusions

\[ V' < 1.81 \text{ TeV} \]
\[ G_{RS} < 1.06 \text{ TeV} \]
Diphoton Resonance Search
Overview

Search for resonant production in $m_{\gamma\gamma}$ distribution
Optimised for scalar production using NWA and LWA

Background is dominated by QCD production of two prompt photons

Selection Criteria

- Leading photon $E_T > 0.4 \ m_{\gamma\gamma}$
- Subleading photon $E_T > 0.3 \ m_{\gamma\gamma}$

Having relative $E_T$ cuts leads to a 10% -> 20% increase in sensitivity.

Data driven background modelling
Smoothly falling distribution fitted to the signal region

$$f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}$$

Background fit performed for $170 \ GeV < m_{\gamma\gamma} < 2000 \ GeV$

Signal modelled with a Double-Sided Crystal Ball function

$200 \ GeV < m_H < 1700 \ GeV$

Dominant uncertainties are from the photon energy measurement and background fit.

Resolution of $m_{\gamma\gamma}$ increases with mass

- 2 GeV at 200 GeV
- 13 GeV at 2 TeV
DIPHOTON

Results

The largest deviation from background only at 750 GeV
Local (global) excess of $3.6 \sigma$ ($2.0 \sigma$) for NWA
Local (global) excess of $3.9 \sigma$ ($2.3 \sigma$) for a width of 45 GeV

At 750 GeV, the mass resolution is 6 GeV

Second largest deviation from background only at 1.6 TeV
Local excess of $2.8 \sigma$ for NWA

Limits are set on the product of fiducial cross-section and branching ratio.
Conclusion
CONCLUSION

Diboson Resonances

Diboson resonances have been probed at the TeV scale
Large number of decay channels probed

A local (global) 3.4 $\sigma$ (2.5 $\sigma$) excess is seen at 2 TeV for diboson resonace in the $qqqq$ channel (only) in Run I
Run II analyses are limited by the current small data set
Expected 2016 dataset should be sufficient to confirm/exclude this excess.

Diphoton Resonance

A local (global) 3.9 $\sigma$ (2.3 $\sigma$) excess is seen at 750 GeV with a width of 45 GeV
A local (global) 2.6 $\sigma$ (1.2 $\sigma$) excess is seen at 760 GeV in the corresponding CMS analyses

All pointing towards 2016 being an exciting year!
Backup Slides
Heavy Vector Triplet (HVT) Model A

- Generic phenomenological Lagrangian
- Introduces a new Heavy Vector Triplet ($W'$, $Z'$)
- Parameters in model A are chosen so as to be similar to the Extended Gauge Model (EGM) which was tested in run 1.
- Branching ratios of $W' \rightarrow WZ, WH$ and $Z' \rightarrow WW, ZH$ are ≈2%.
- Widths of $W'$ and $Z'$ are approximately 2.5% of the pole mass.

Bulk RS Graviton

- Extends the original Randall-Sundrum model with warped extra dimensions.
- Allows SM fields to propagate through the bulk.
- Parameterised by the coupling constant $\kappa/M_{Pl} = 1$.
- Considerable branching ratios to $WW$ (17%) and $ZZ$ (9%).
- Width of $G_{RS}$ is approximately 10% of the pole mass.
DIBOSON

Jet Definitions

**Large-R Jets (J)**
- anti-$k_T$ with $R = 1.0$
- Boson tagged
- Trimmed

**Boson Tagging**
- $D_2^{(\beta=1)}$
- 50% boson efficiency
- 90% QCD rejection.

**Trimming**
- Large-R jet reclustered using anti-$k_T R = 0.2$
- Discard sub-jets with $p_T < 5\%$ of the original jet.
- Large-R 4 momentum taken as the sum of the remaining subjets.

This is the default jet collection used in the diboson resonance searches. The dominant uncertainty in a majority of the diboson resonance searches are due to the mass and energy measurements of these jets.

**Small-R Jets (j)**
- anti-$k_T$ with $R = 0.4$
- Used to identify other QCD activity.

**Track-jets**
- anti-$k_T$ with $R = 0.2$
- Tracks used must have $p_T > 0.4$ GeV.
- b-tagged, 70% efficiency.
- Associated to large-R jets.
Run I qqqq analysis
Two large-R jet signal candidate
Search for diboson resonances with boson-tagged jets

$W', Z', G_{RS} \rightarrow VV \rightarrow qqqq$

Selection Criteria
- Trigger: single large-R jet, $E_T > 360$ GeV
- No charged leptons
- 2 large-R jets
- $p_T^{J1} > 450$ GeV
- $p_T^{J2} > 200$ GeV
- $|m_V - m_{JJ}| < 15$ GeV
- Reject jets in the range $110$ GeV $< m_j < 140$ GeV
- $E_T^{\text{miss}} < 250$ GeV

Additional boson tagging
- Require the number of charged tracks with $p_T > 0.5$ GeV associated with the large-R jet, $N_{trk} < 30$.
- Reject large-R jets with more than 1 b-tagged track jet.

Dominant uncertainties relate to large-R jet mass and energy measurement.

QCD multijet background dominates.
Search for diboson resonances in the $\nu\nuqq$ final state

**Selection Criteria**

- Trigger: $E_T^{\text{miss}} > 80$ GeV
- $E_T^{\text{miss}} > 250$ GeV
- $p_T^{\text{miss}} > 30$ GeV
- At least one jet with $p_T^j > 200$ GeV
- $|m_V - m_j| < 15$ GeV
- No charged leptons
- $\Delta\phi(E_T^{\text{miss}}, j) > 0.6$
- $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < \pi/2$

The background is dominated by V+jets and top quark pair production.

Dominant uncertainties relate to large-R jet mass and energy measurement.
The background is dominated by $V+$jets and top quark pair production.

Dominant uncertainties relate to large-R jet mass and energy measurement.

Limits are set on production cross-section times branching ratio for the three models.

The HVT model is excluded for $m_{V'} < 1.6$ TeV.

A heavy Higgs model is also tested.
Search for diboson resonances in the $lvqq$ final state

**Selection Criteria**

- Single lepton trigger
- $E_T^{\text{miss}} > 100$ GeV
- Exactly one lepton
- $p_T^{l\nu} > 200$ GeV
- $|m_{lvJ} - m_V| < 13$ GeV
- No small-R jets tagged as b-jets $\Delta R > 1.0$ from $V$

The background is dominated by $V+$jets.

Heavy Higgs model also tested.

Dominant uncertainties relate to the modelling of the dominant background derived from control regions.
The background is dominated by $V$+jets.

Dominant uncertainties relate to the modelling of the dominant background derived from control regions.

$G_{RS}$ excluded below 1060 GeV.

Heavy Higgs model also tested.
Search for diboson resonances in the $llqq$ final state

**Selection Criteria**

- Single lepton trigger
- Exactly two SF lepton
- $p_T^\mu, E_T^e > 25$ GeV
- $p_T^J > 200$ GeV
- $83$ GeV < $m_{ee}$ < $99$ GeV
- $66$ GeV < $m_{\mu\mu}$ < $116$ GeV

The background is dominated by Z+jets.

Heavy Higgs model also tested.
Not optimized for this signal.

Dominant uncertainties relate to large-R jet mass and energy measurement.
Background is dominated by Z+jets.

Dominant uncertainties relate to large-R jet mass and energy measurement.

$W'$ excluded below 1400 GeV

$G_{RS}$ excluded below 850 GeV

Heavy Higgs model also tested. Not optimized for this signal.
Search for new resonances decaying to $VH$, in the $llbb$, $lvbb$ and $vvbb$ final states

$A, W', Z', G_{RS} \rightarrow VH \rightarrow llbb, lvbb, vvbb$

**Selection Criteria**

- At least one jet with $p_T^j > 250$ GeV
- $75$ GeV $< m_j < 145$ GeV
- At least one of the two leading track jets associated to the large-R jet must be b-tagged
- Signal regions split by number of b-tags

The background is dominated by V+jets.

Dominant uncertainties relate to large-R jet mass and energy measurement.

Heavy CP-odd scalar model also tested.

As well as the previously described HVT model A, model B is tested.
In this model fermionic couplings are highly suppressed.