ATLAS Searches for VV/Vγ Resonances

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on behalf of the ATLAS collaboration
Introduction

- The Standard Model (SM) and the recently discovered Higgs boson address issues in our understanding of nature and provide a more solid basis on which to continue our exploration.

- A plethora of precision measurements and limit settings with data from the Large Hadron Collider (LHC) has shown no (significant) indication of new physics.

- While the SM describes particle interactions for energy scales up to a few hundred GeV, a number of issues, such as the sensitivity of the Higgs mass to radiative corrections indicate either extreme fine-tuning or the presence of new physics.

- **Where is the new physics?**

- Many theories attempt to provide answers:
  - Predict heavy resonances decaying to heavy quarks or bosons
    - This talk covers $VV/V\gamma$, where $V = W/Z$.

- Many issues can be addressed:
  - The hierarchy problem
  - Can fundamental scalars exist in nature?
  - Do interactions unify at some high energy scale?
  - Where do fermion properties come from?
  - Dark matter and gravity can be incorporated.
Composite Higgs Models

- Higgs is not an elementary particle but has structure
- Bound state of a new force that manifests itself at O(1) TeV scale
- Predicts resonances related to this new dynamics at O(1) TeV scale
- Stabilizes the mass and solves the hierarchy problem
- Dark matter can be incorporated naturally in composite Higgs models

**Final states:** *neutral/charged, narrow or large width, produced via gluon-gluon fusion (ggF) or vector boson fusion (VBF)*
Heavy Vector Triplets (HVT)

- Could appear in composite Higgs models but also in weakly coupled theories

- A simplified phenomenological Lagrangian where only the relevant parameters that control the mass of the resonance and the interactions involved in its production and decay are retained

- Models according to the typical strength of vector boson interactions ($g_V$) and the dimensionless coefficients ($c_i$):
  - **Model A**: weakly coupled vector resonances from extension of the gauge group, $g_V \sim 1$, $c_H \sim -g^2/g_V^2$, $c_F \sim 1$
  - **Model B**: produced in a strong scenario (composite Higgs models), $1 < g_V \leq 4\pi$, $c_H \sim c_F \sim 1$

- From an experimental perspective, models A and B represent different cross sections

- **Final states**: neutral or charged

- Narrow spin-1 resonances

- $q\bar{q}$ or VBF production

*HVT theory 10.1007/JHEP09(2014)060*
Warped Extra Dimensions

- The so called Randall-Sundrum (RS) models
  - Gravity propagates in a warped extra dimension
  - The SM fields are constrained to one brane
  - It provides a solution to the hierarchy problem

- Bulk graviton models allow SM particles into 5D-bulk
  - Overlap of 5D profiles at TeV-brane determine particle masses

- The most distinctive feature of this scenario is the existence of spin-2 Kaluza-Klein (KK) gravitons whose masses and couplings to the SM are set by the TeV scale

- Neutral final states
- ggF production is dominant
- Narrow width, depends on the $k/\tilde{M}_{Pl}$ choice, where $\tilde{M}_{Pl} = M_{Pl}/8\pi$ is the reduced Planck scale and $k$ is the curvature scale of the extra dimension
Di-Boson Searches

- Di-boson searches are highly motivated and have been proven fruitful in the past (Higgs discovery)
- Many theories predict di-boson resonances with different properties (charge, spin, width, production mechanism)
- **Simple methodology**: search for excesses above the background

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Model independent searches are important!
V Decays & Channels To Be Covered

**Leptonic decays (ll, lv, vv)**
- **Small branching ratios:**
  - $\text{BR}(W \rightarrow lv) = 33.3\%$
  - $\text{BR}(Z \rightarrow ll) = 10.2\%$
  - $\text{BR}(Z \rightarrow vv) = 20.5\%$
- **Cleaner final states through leptons reconstruction**
- **Perform better at low masses**

**Hadronic (qq)**
- **Large branching ratios:**
  - $\text{BR}(W \rightarrow qq) = 66.6\%$
  - $\text{BR}(Z \rightarrow qq) = 69.2\%$
- **Background estimation is trickier**
- **Reconstruction using anti-kt jets**
- **Perform better at high masses where SM backgrounds fall off**

<table>
<thead>
<tr>
<th>Channel to be covered</th>
<th>References</th>
<th>Luminosity (fb$^{-1}$)</th>
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<tbody>
<tr>
<td>$VV \rightarrow qqqq$</td>
<td>ATLAS-EXOT-2016-19</td>
<td>36.1</td>
</tr>
<tr>
<td>$WV \rightarrow lvqq$</td>
<td>ATLAS-CONF-2017-051</td>
<td>36.1</td>
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<tr>
<td>$ZV \rightarrow llqq/vvqq$</td>
<td>ATLAS-EXOT-2016-29</td>
<td>36.1</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow ll\gamma/qq\gamma$</td>
<td>Phys.Lett. B764 (2017) 11-30</td>
<td>3.2</td>
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Hadronic V Decays

Final state decay products can be highly energetic if search particle is very massive

- Angular separation
  \[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \approx 2m/p_T \]

- **Resolved Regime**: relatively low momentum, one small-R jet (distance parameter \( R = 0.4 \)) is reconstructed for each quark

- **Boosted Regime**: relatively high momentum, boson is reconstructed as a large-R jet (\( R = 1.0 \)), it is denoted as \( J \)

- Novel techniques have been developed for boosted objects identification
Towards Boosted Boson Tagging

**Grooming technique** (pile-up & soft QCD subtraction):

- **Trimming**
  - Remove constituents with $p_{T}^{\text{constituent}}/p_{T}^{\text{jet}} < 5\%$

- Possible due to the fine calorimeter granularity
  ~0.025 (EM) to 0.1 (HAD)
Very energetic jets with prong structure have small angular separation between their constituents → the missing calorimeter information makes the mass resolution worse.

The tracker information can improve the mass resolution in the high $p_T$ region.

A combination of the calorimeter and track information is used:

$$m_{\text{comb}} = \frac{\sigma_{\text{calo}}^{-2} m_{\text{calo}} + \sigma_{\text{TA}}^{-2} m_{\text{TA}}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}}$$

where

$$m_{\text{TA}} = m_{\text{trk}} \times \frac{p_T^{\text{calo}}}{p_T^{\text{trk}}}.$$
Substructure Variable

- Energy Correlation Functions (ECF)

\[ E_{\text{CF}1} = \sum_i p_{T,i} \]
\[ E_{\text{CF}2} = \sum_{ij} p_{T,i} p_{T,j} \Delta R_{ij} \]
\[ E_{\text{CF}3} = \sum_{ijk} p_{T,i} p_{T,j} p_{T,k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki} \]

- Substructure Variable:

\[ D_{2}^{\beta=1} = E_{\text{CF}3} \left( \frac{E_{\text{CF}1}}{E_{\text{CF}2}} \right)^3 \]

- Different working points (w.p.): providing different signal efficiency, e.g. 50%, 80%
- Variable cuts: according to the jet \( p_T \)
VV Boosted Searches

- At least one hadronic V decay
- Hadronic W and Z signal regions partially overlap
- Different VV final states are orthogonal
- Final discriminant is the invariant VV mass
  - Exception: the vvqq channel uses the transverse mass because it is not possible to fully reconstruct the mass due to the presence of neutrinos

\[
m_T = \sqrt{(E_{T,J} + E_{T,\text{miss}}^\text{miss})^2 - (\mathbf{p}_{T,J} + \mathbf{E}_{T,\text{miss}}^\text{miss})^2}
\]
VV Semi-Leptonic Production Mechanism Categorization

Categories:
- **VBF** (is prioritized)
- **Drell-Yan (DY)**: \( qq \) or \( ggF \) production

**VBF signature:**
- Two quarks, i.e. small-R jets, are expected to be found in opposite pseudo-rapidity hemisphere

**DY production:**
- Absence of VBF topology
VV Semi-Leptonic Production Mechanism Categorization

Analysis:
1. Search for production mechanism
2. Search for VV decays

VV → lvqq event display:
- Electron $p_T = 777$ GeV
- $E_T^{\text{miss}} = 362$ GeV
- Large-$R$ jet: $m = 81$ GeV, $p_T = 1118$ GeV
- $m(WV) = 2.759$ TeV
- $VBF: m_{\text{tag}}(jj) = 812$ GeV, $\Delta \eta_{\text{tag}}(jj) = 5.6$

Note:
The two boson candidates are “balanced”, each boson holds ~half of the energy
VV Semi-Leptonic Selection

- Search for a leptonic V decays:
  - $W \rightarrow lv$ or $Z \rightarrow ll$ or $Z \rightarrow vv$

- Search for a hadronic V decay:
  - Merged analysis is prioritized
    - Large-R jet: $p_T > 200$ GeV, $|\eta| < 2.0$
    - Mass and $D_2$ cuts:
      - 50% w.p.: High Purity (HP)
      - 80% w.p.: Low Purity (LP)

- Resolved analysis (if the event failed the merged selection)
  - Two small-R jets
  - Invariant mass compatible with a V mass
  - Prioritizing $Z \rightarrow bb$ events increases the sensitivity
VV Semi-Leptonic Background Estimate

Background composition:
- V+jets
- ttbar
- Smaller contributions from SM dibosons, single top and QCD

For each VV channel, set of signal and control regions are formed for:
- DY, VBF
- WW, WZ, ZZ, ZW
- HP, LP, Resolved (not for the vvqq)
A Few ... VV Semi-Leptonic Final Discriminants

\( WZ \rightarrow lvqq \) example (VBF category)

\( ZZ \rightarrow llqq \) example (DY category)

\( ZZ \rightarrow vvqq \) example (DY category)
VV Semi-Leptonic Scalar Limits

**VBF production**

**DY production**
VV Semi-Leptonic HVT Limits

**VBF production**

**DY production**
VV Semi-Leptonic Graviton Limits
VV → JJ
VV $\rightarrow$ JJ Background Estimation

- Multijet background dominates
- High purity signal regions only
- It is modeled with: $\frac{dn}{dx} = p_1 (1 - x)^{(p_2 - \xi) p_3} x^{-p_3}$

where $x = m_{jj}/\sqrt{s}$, $p_1$ is a normalization factor, $p_2$ and $p_3$ are dimensionless shape parameters, $\xi$ is a constant chosen to remove the correlation between $p_2$ and $p_3$ in the fit.
VV → JJ Results
VV Results
VV Results

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

95\% C.L. exclusion limits

- HVT model B \( g_v = 3 \)
- Observed
- Expected
- \( qqqq \)
- \( lvqq \)
- \( llqq \)
- \( vvqq \)
$X^0 \rightarrow Z\gamma$ Searches

- $Z \rightarrow e^+e^-/\mu^+\mu^-/J$ and $p_T(\gamma) > 250$ GeV

- Main backgrounds:
  - Leptonic $Z$ analysis: non-resonant $Z+\gamma$, $Z+$jet
  - Hadronic $Z$ analysis: $\gamma+$jet, multijet, $V+$jet
The mass distribution is parametrized:

\[ f_{\text{bkg}}(m) = N(1-x^k)p_1+\xi p_2x^p \]

N is a normalization factor, \( x = m/\sqrt{s} \), \( k = 1/3(1) \) for the leptonic (hadronic) analysis, \( \xi = 0 (10) \) in the leptonic (hadronic) analysis, \( p_1 \) and \( p_2 \) are dimensionless shape parameters.

Results with 3.2 fb\(^{-1}\) only!
Summary

- Latest ATLAS Run II searches for VV/Vγ resonances presented
- Di-boson searches are motivated by multiple models and they are a direct way to explore the TeV scale
- These searches are experimentally challenging
- Boosted object tagging is an important key to probe high mass new physics and an active area of development
- No evidence for heavy resonance production at ATLAS ... yet
- More data are being recorded now, stay tuned

Thank you for your attention!
Back-up Slides
Luminosity

- Run II at $\sqrt{s} = 13$ TeV started in 2015
- Recorded 3.2 fb$^{-1}$ in 2015, 32.9 fb$^{-1}$ in 2016
- Data taking efficiency > 92.4%
- 2017 data taking has started, ~45 fb$^{-1}$ are expected this year
Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 \( \sqrt{s} = 7, 8, 13 \text{ TeV} \)

Large-R Jet Uncertainties

The relative uncertainty is determined using the ratio of calorimeter to track-jet quantities:

\[ r_{\text{track jet}}^{p_T} = \frac{p_{\text{T, jet}}}{p_{\text{T, track jet}}}, \quad r_{\text{track jet}}^{m} = \frac{m_{\text{jet}}}{m_{\text{track jet}}}. \]

Double ratios are constructed:

\[ R_{r_{\text{track jet}}}^{p_T} = \frac{r_{\text{track jet}}^{p_T, \text{data}}}{r_{\text{track jet}}^{p_T, \text{MC}}}, \quad R_{r_{\text{track jet}}}^{m} = \frac{r_{\text{track jet}}^{m, \text{data}}}{r_{\text{track jet}}^{m, \text{MC}}}. \]

**Uncertainties:**

- **Baseline:** difference between data and MC
- **Modeling:** difference between MC generators
- **Tracking:** related to track reconstruction efficiency, impact parameter resolution, track momentum calibration and reconstruction of fake tracks
Performance @13 TeV

**ATLAS** Preliminary

- $\sqrt{s} = 13$ TeV, 33.9 fb$^{-1}$
- $-2.47 < \eta < 2.47$

**e identification efficiency**

Data: full, MC: open

**Muon p_T scale**


**ET_{miss} scale**

*JETM-2016-008*
Performance @13 TeV

**EGAM-2016-003**

- $\sqrt{s} = 13$ TeV, $L_{int} = 11.6$ fb$^{-1}$

**ATLAS Preliminary**

**In-situ jet calibration**

**JETM-2017-003**

- $\sqrt{s} = 13$ TeV, $L_{int} = 11.6$ fb$^{-1}$

**ATLAS Preliminary**

- $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$
- Unconverted $\gamma$
- Converted $\gamma$
- Data 2016
- Corrected $Z \rightarrow ll\gamma$ MC
- $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$
- Flav. composition, unknown composition
Additional VV Plots