Optimizing Selection and Sensitivity Results for VV->lvqq, 6.5 pb⁻¹, 13 TeV Data

Hallie Stidham
Supervisor: Dr. Kalliopi Iordanidou
2015 Columbia University REU
July 30, 2015

Home Institution: High Point University
Summary

- Introduction
  - CERN and the Large Hadron Collider
  - The ATLAS Experiment
  - Particles
- Data and Monte Carlo Samples
- VV Resonance and Selection
  - Resonance and Decay
  - Selection
- Selection Optimization
  - Selection & Extrapolations
  - Significance Plots & Trigger Studies
  - Multivariate Analysis
  - Topology Plots
- Conclusions
CERN

- In 1954 twelve countries ratified the European Council for Nuclear Research, CERN
- Located near Geneva, Switzerland along Franco-Swiss border
- Today there are 21 member states
- Focused on particle physics research
- Home to the Large Hadron Collider (LHC)
Large Hadron Collider

• Largest and most powerful particle accelerator in the world
• 27 kilometer ring that holds superconducting magnets
• High energy particle beams travel in opposite directions
• Collisions at 4 main particle detectors, ALICE, ATLAS, CMS, LHCb
• Run 1: March 2010-February 2013
• Run 2: April 2015-present
The ATLAS Experiment

• “A Toroidal LHC ApparatuS”, large general purpose particle detector
• 7,000 tonnes, 46m x 25m x 25m
• Four major components
  ▫ Inner Detector: measures momentum of charged particles
  ▫ Calorimeter: measures energies carried by particles
  ▫ Muon Spectrometer: identifies and measures momenta of muons
  ▫ Magnet System: bends charged particles for momentum measurement
Particles

• Leptons
  ▫ Elementary particles, do not undergo strong interactions
  ▫ Six flavors, three generations
    • First Generation: Electron $e^-$ & Electron Neutrino $\nu_e$
    • Second Generation: Muon $\mu^-$ & Muon Neutrino $\nu_\mu$
    • Third Generation: Tau $\tau^-$ & Tau Neutrino $\nu_\tau$
    • For all generations
      • $e^-, \mu^-, \tau^-$: negative charge, elementary particle
      • $\nu_e, \nu_\mu, \nu_\tau$: no electric charge
      • Anti-Particles: Positron $e^+$, Antimuon $\mu^+$, Antitau $\tau^+$
        • Same mass as respective particle, opposite charge
Particles cont.

• **Gauge Bosons**
  ▫ **Type of vector boson**
  ▫ **Three types**
    • Photons: carry electromagnetic interaction
    • W & Z Bosons: carry weak interaction
    • Gluons: carry strong interaction

• **Missing Transverse Energy (MET)**
  ▫ Used to deduce presence of non-detectable particles (ex: neutrino)
Particles cont.

• Hadrons
  ▫ Composite particles made of quarks
  ▫ Held together by strong force
  ▫ Two categories: Baryons & Mesons
    • Baryons (ex: protons and neutrons)
      • Made of three quarks
    • Mesons (ex: pion)
      • One quark, one antiquark

• Jets
  ▫ High-energy quark transformed into spray of hadrons
  ▫ Most commonly used in ATLAS
    • Regular Jets: 0.4 distance parameter
    • Large-R Jets: 1.0 distance parameter
      • Boosted Jets
Resonance and Decay

- Resonance
  - Peak at a particular mass when two particles’ cross sections interactions are examined as a function of energy
  - Cause: creation of a particle whose mass-energy is energy of resonance
  - Described by mass spectrum of dispersion type
  - Maximum = resonance mass $m$
  - Spectrum width = probability of resonance decay $\Gamma$
    - Does not exceed $mc^2$
Resonance and Decay cont.

- VV Resonance
  - See Feynman diagram, studied in lvqq final state
  - Example of how signal bump should show above the background, if signal exists
Data and Monte Carlo Samples

- 6.5 pb$^{-1}$ at 13 TeV
- Signal
  - Signal, Heavy Vector Triplet
- Background
  - W + Jets
  - Z + Jets
  - ttbar
- No multijet or standard model diboson samples, estimated to be very small from Run 1
- Run 1 Multijets Extrapolation
  - 29 recorded events with luminosity of 20.3 fb$^{-1}$ at 8 TeV -> average of 6 events ± 3 events
Monte Carlo Scale

- Signal -> HVT Signal 2 TeV
  - MadGraphPythia

<table>
<thead>
<tr>
<th>Monte Carlo Sample Number</th>
<th>Sample Name</th>
<th>Cross Section (pb(^{-1}))</th>
<th>Filter Efficiency</th>
<th>Initial Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>301389</td>
<td>Signal</td>
<td>0.003853</td>
<td>1</td>
<td>1.9600000e+04</td>
</tr>
<tr>
<td>361100</td>
<td>W(^+) \rightarrow e(^+)(\nu)</td>
<td>11302.00</td>
<td>1</td>
<td>3.391847e+10</td>
</tr>
<tr>
<td>361101</td>
<td>W(^+) \rightarrow \mu(^+)(\nu)</td>
<td>11302.00</td>
<td>1</td>
<td>3.391694e+10</td>
</tr>
<tr>
<td>361102</td>
<td>W(^+) \rightarrow \tau(^+)(\nu)</td>
<td>11302.00</td>
<td>1</td>
<td>3.391262e+10</td>
</tr>
<tr>
<td>361103</td>
<td>W(^-) \rightarrow e(^-)(\nu)</td>
<td>8280.00</td>
<td>1</td>
<td>1.654872e+10</td>
</tr>
<tr>
<td>361104</td>
<td>W(^-) \rightarrow \mu(^-)(\nu)</td>
<td>8280.00</td>
<td>1</td>
<td>1.656678e+10</td>
</tr>
<tr>
<td>361105</td>
<td>W(^-) \rightarrow \tau(^-)(\nu)</td>
<td>8280.00</td>
<td>1</td>
<td>1.656333e+10</td>
</tr>
<tr>
<td>361106</td>
<td>Z \rightarrow e(^+) + e(^-)</td>
<td>1900.00</td>
<td>1</td>
<td>3.801334e+09</td>
</tr>
<tr>
<td>361107</td>
<td>Z \rightarrow \mu(^+) + \mu(^-)</td>
<td>1900.00</td>
<td>1</td>
<td>3.800993e+09</td>
</tr>
<tr>
<td>361108</td>
<td>Z \rightarrow \tau(^+) + \tau(^-)</td>
<td>1900.00</td>
<td>1</td>
<td>3.800333e+09</td>
</tr>
<tr>
<td>410000</td>
<td>ttbar</td>
<td>831.76</td>
<td>0.543</td>
<td>1.9970000e+06</td>
</tr>
</tbody>
</table>

Scale Factor = \(\frac{\text{Cross Section} \times \text{Filter Efficiency} \times \text{Luminosity}}{\text{Initial Events}}\)
Selection

• Tight Electron
  ▫ $P_T > 25$ GeV, $\eta < 2.47$, tight working point

• Medium Muon
  ▫ $P_T > 25$ GeV, $\eta < 2.5$, medium working point

• Level 1 Trigger (L1 Trigger)
  ▫ Lowest level trigger

• Boosted case
  ▫ Close Quarks
  ▫ Reconstructions identified as Large-R Jets
Selection cont.

- **Baseline Selection**
  - Tight electron, medium muon, L1 Trigger
  - MET > 30 GeV
  - Lepton Neutrino $P_T > 100$ GeV
  - At least on Large-R Jet with $P_T > 100$ GeV
Selection Optimization

- Additional selection to study sensitivity of signal selection against background
- Increase in MET cut to MET > 100 GeV
  - Clean selection of quantum chromo dynamics (QCD) contamination
- Large-R Jets mass between 60-105 GeV
- Large-R Jet $P_T > 200$ GeV
- Lepton Neutrino $P_T > 200$ GeV
MET Plots

MET with before cuts, low mass excess is QCD

MET after > 100 GeV cut
Extrapolations of Signal and Background at various luminosities

- Reflective of how yields will progress as luminosity increases
- Expect to get up to 100 fb\(^{-1}\) by the end of Run 2 ~3 years

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>6.5 pb(^{-1})</th>
<th>28 pb(^{-1})</th>
<th>1 fb(^{-1})</th>
<th>5 fb(^{-1})</th>
<th>10 fb(^{-1})</th>
<th>50 fb(^{-1})</th>
<th>100 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJets</td>
<td>6.61</td>
<td>28.47</td>
<td>101.68</td>
<td>508.38</td>
<td>1016.76</td>
<td>5083.78</td>
<td>10167.6</td>
</tr>
<tr>
<td>ZJets</td>
<td>0.11</td>
<td>0.46</td>
<td>1.65</td>
<td>8.26</td>
<td>16.52</td>
<td>82.58</td>
<td>165.15</td>
</tr>
<tr>
<td>ttbar</td>
<td>10.93</td>
<td>47.09</td>
<td>168.16</td>
<td>840.81</td>
<td>1681.61</td>
<td>8408.06</td>
<td>16816.10</td>
</tr>
<tr>
<td>Signal</td>
<td>0.01</td>
<td>0.03</td>
<td>0.10</td>
<td>0.49</td>
<td>0.98</td>
<td>4.90</td>
<td>9.80</td>
</tr>
<tr>
<td>Total Background</td>
<td>17.65</td>
<td>76.02</td>
<td>271.49</td>
<td>1357.44</td>
<td>2714.88</td>
<td>13574.40</td>
<td>27148.80</td>
</tr>
<tr>
<td>Significance Estimate</td>
<td>0.01</td>
<td>0.17</td>
<td>0.32</td>
<td>0.71</td>
<td>1.00</td>
<td>2.24</td>
<td>3.17</td>
</tr>
</tbody>
</table>

\[
\text{Significance} = \sqrt{2 \times (s + b) \times \log(1 + s/b) - s}
\]
Extrapolations of Signal and Background at various luminosities

### Original Cuts plus Large-R Jet mass between 60-105 GeV

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>6.5 pb⁻¹</th>
<th>28 pb⁻¹</th>
<th>1 fb⁻¹</th>
<th>5 fb⁻¹</th>
<th>10 fb⁻¹</th>
<th>50 fb⁻¹</th>
<th>100 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJets</td>
<td>6.02</td>
<td>25.94</td>
<td>92.64</td>
<td>463.22</td>
<td>926.44</td>
<td>4632.21</td>
<td>9264.42</td>
</tr>
<tr>
<td>ZJets</td>
<td>0.11</td>
<td>0.46</td>
<td>1.65</td>
<td>8.26</td>
<td>16.51</td>
<td>82.58</td>
<td>165.15</td>
</tr>
<tr>
<td>ttbar</td>
<td>10.14</td>
<td>43.69</td>
<td>156.03</td>
<td>780.14</td>
<td>1560.27</td>
<td>7801.34</td>
<td>15602.70</td>
</tr>
<tr>
<td>Signal</td>
<td>0.01</td>
<td>0.03</td>
<td>0.09</td>
<td>0.45</td>
<td>0.91</td>
<td>4.53</td>
<td>9.06</td>
</tr>
<tr>
<td>Total Background</td>
<td>16.27</td>
<td>70.09</td>
<td>250.32</td>
<td>1251.61</td>
<td>2503.22</td>
<td>12516.10</td>
<td>25032.20</td>
</tr>
<tr>
<td>Significance Estimate</td>
<td>0.08</td>
<td>0.16</td>
<td>0.31</td>
<td>0.68</td>
<td>0.96</td>
<td>2.16</td>
<td>3.05</td>
</tr>
</tbody>
</table>

### Original Cuts plus Large-R Jet mass between 60-105 GeV & D2 > 1.4

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>6.5 pb⁻¹</th>
<th>28 pb⁻¹</th>
<th>1 fb⁻¹</th>
<th>5 fb⁻¹</th>
<th>10 fb⁻¹</th>
<th>50 fb⁻¹</th>
<th>100 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJets</td>
<td>3.00</td>
<td>12.92</td>
<td>46.15</td>
<td>230.76</td>
<td>461.52</td>
<td>2307.62</td>
<td>4615.24</td>
</tr>
<tr>
<td>ZJets</td>
<td>0.04</td>
<td>0.16</td>
<td>0.58</td>
<td>2.91</td>
<td>5.83</td>
<td>29.15</td>
<td>58.29</td>
</tr>
<tr>
<td>ttbar</td>
<td>2.53</td>
<td>10.88</td>
<td>38.85</td>
<td>194.24</td>
<td>388.48</td>
<td>1942.41</td>
<td>3884.82</td>
</tr>
<tr>
<td>Signal</td>
<td>0.002</td>
<td>0.01</td>
<td>0.04</td>
<td>0.18</td>
<td>0.35</td>
<td>1.76</td>
<td>3.53</td>
</tr>
<tr>
<td>Total Background</td>
<td>5.56</td>
<td>23.96</td>
<td>85.58</td>
<td>427.92</td>
<td>855.84</td>
<td>4279.18</td>
<td>8558.35</td>
</tr>
<tr>
<td>Significance Estimate</td>
<td>0.05</td>
<td>0.10</td>
<td>0.19</td>
<td>0.42</td>
<td>0.60</td>
<td>1.34</td>
<td>1.89</td>
</tr>
</tbody>
</table>
Significance Plots

- Ratio of signal sample with respect to background
- Signal is 2 TeV resonance signal

Significance plot of Large-R Jet mass between 60-105 GeV
Significance Plots cont.

Significance plot of Large-R Jet D2

Shows optimal cut is $D2 < 1.4$

Significance plot of $P_{T}^{lv}/M_{lvJ}$

Shows optimal cut is $P_{T}^{lv}/M_{lvJ} > 0.5$
Trigger Studies

- "Old Trigger" is passL1_EM18VH and passL1_MU10
  - L1 = Level 1 Trigger
- "New Trigger" is passHLT_j360_a10_sub and passHLT_j460_a10_sub in addition to old trigger
  - HLT = High Level Trigger
  - "a" = AntiKt4LCTopo
  - A10 = Large-R Jet
  - 10 = size of cone
  - 460 = $P_T$ threshold
  - Sub = pile-up subtraction
    - Subtracts interference with objects
Trigger Studies

Large-R Jet mass between 60-105 GeV & D2 > 1.4

<table>
<thead>
<tr>
<th>Approximate % Change in Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New Trigger</strong></td>
</tr>
<tr>
<td>Significance</td>
</tr>
<tr>
<td>0.08</td>
</tr>
<tr>
<td>0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Approximate % Change in Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old Trigger</strong></td>
</tr>
<tr>
<td>Significance</td>
</tr>
<tr>
<td>0.08</td>
</tr>
<tr>
<td>0.06</td>
</tr>
</tbody>
</table>
Multivariate Analysis

• 2 TeV targeted selection using Boosted Decision Trees

• Input Variables
  ▫ Large- R Jet Mass (FJMass)
  ▫ Lepton Neutrino $P_T$ (lvPT)
  ▫ Lepton Neutrino - Large-R Jet $\eta$ (lvFJeta)
  ▫ Lepton Neutrino - Large-R Jet $\phi$ (lvFJphi)
  ▫ Large-R Jet $P_T$ (FJPt)
  ▫ Large-R Jet $y$ (FJy)
  ▫ Large-R Jet $D_2$ (FJD2)
Multivariate Analysis Input Variables
Multivariate Analysis cont.

- Significance of 3.667 with optimal cut value of -0.020
- Large-R Jet $P_T$ is best discriminant against background

<table>
<thead>
<tr>
<th>Evaluation results ranked by best signal efficiency and purity (area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA Method:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>BDT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ranking input variables (method specific)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking result (top variable is best ranked)</td>
</tr>
<tr>
<td>Rank</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>
Multivariate Analysis cont.

Cut Efficiencies Plot

Signal and background efficiency for specific Boosted Decision Tree value

BDT Output Distributions

Shows difference between signal and background due to their responses to the Boosted Decision Tree
Topology Plots

- Show agreement between data and Monte Carlo
- No cuts made on D2 for plot of Large-R Jet D2
- No cuts made on $P_{T}^{lv}/M_{lvJ}$ for plot of $P_{T}^{lv}/M_{lvJ}$
- All other plots made using baseline cuts
Topology Plots cont.

Large-R Jet $\eta$

ATLAS Work in Progress
\[ \int L = \sim 6.5 \text{ pb}^{-1}, \sqrt{s} = 13 \text{ TeV} \]

- ZJets
- WJets
- t\bar{t}
- Signal
- Data

Large-R Jet $P_T$

ATLAS Work in Progress
\[ \int L = \sim 6.5 \text{ pb}^{-1}, \sqrt{s} = 13 \text{ TeV} \]

- ZJets
- WJets
- t\bar{t}
- Signal
- Data

Large-R Jet $D_2$

ATLAS Work in Progress
\[ \int L = \sim 6.5 \text{ pb}^{-1}, \sqrt{s} = 13 \text{ TeV} \]

- ZJets
- WJets
- t\bar{t}
- Signal
- Data

Large-R Jet Mass

ATLAS Work in Progress
\[ \int L = \sim 6.5 \text{ pb}^{-1}, \sqrt{s} = 13 \text{ TeV} \]

- ZJets
- WJets
- t\bar{t}
- Signal
- Data
Topology Plots cont.

Lepton Neutrino $\eta$

Lepton Neutrino $P_T$

Lepton Neutrino Mass

Lepton Neutrino $P_{T}^{\nu}/M_{\nu J}$

Hallie Stidham

July 30, 2015
Topology Plots cont.

Large-R Jet $y$

Number of Large-R Jets

$ATLAS$ Work in Progress

$\int L = \sim 6.5 \text{ pb}^{-1}, \sqrt{s} = 13 \text{ TeV}$
Conclusions

• Cut based vs. Multivariate Analysis
• Multivariate analysis gives better sensitivity results
  ▫ More difficult to estimate systematic uncertainties using multivariate analysis approach
• Cut based is proposed method
  ▫ Final cuts
    • Tight electron, medium muon
    • L1 Trigger
    • MET > 100 GeV
    • Lepton Neutrino $P_T > 200$ GeV
    • At least 1 Large-R Jet with $P_T > 200$ GeV
    • Large-R Jet $D^2 < 1.4$
    • $P_{lv}/M_{lvJ} > 0.5$
• I would like to Poppy for her mentorship and the Columbia REU Program and Prof. Parsons for this opportunity!