Vector boson scattering and triboson studies at ATLAS

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May 25, 2017
### Periodic Table of SM Particles

- **Particle physics:** study fundamental particles and their interactions

- **Particles in the SM:**
  - 12 matter particles – spin-$\frac{1}{2}$ fermions
  - 4 force carrier particles – spin-1 bosons (vector bosons)
    - Electromagnetic ($\gamma$), weak ($W^+/W^-$, $Z$) and strong ($g$)
    - Electromagnetic and weak forces unified to electroweak force
  - 1 Higgs particle – spin-0 boson (scalar boson)
Spontaneous Symmetry Breaking in SM

A complex Higgs field (2 DOFs)

Massless Goldstone boson

Massive Higgs boson
Spontaneous Symmetry Breaking in SM

Massless Goldstone boson  Massive Higgs boson

A complex Higgs field (2 DOFs)

Two transverse modes of massless vector field:

Complex scalar field (2 degrees of freedom):
Spontaneous Symmetry Breaking in SM

A complex Higgs field (2 DOFs)

Two transverse modes of massless vector field:

Massless Goldstone boson

Complex scalar field (2 degrees of freedom):

Massive Higgs boson

Massless Goldstone boson

Two transverse modes + longitudinal mode of massive vector boson:

Massive vector boson

Higgs boson

Massless vector boson

Higgs field

Massive vector boson
Spontaneous Symmetry Breaking in SM

A complex Higgs field (2 DOFs)

Massless Goldstone boson

Massive Higgs boson

Two transverse modes of massless vector field:

Complex scalar field (2 degrees of freedom):

Two transverse modes + longitudinal mode of massive vector boson:

Massless Goldstone boson

Higgs field

Massive vector boson

Higgs boson

Massless Goldstone boson is “eaten” by massless vector boson and becomes its longitudinal mode -- the Higgs mechanism
EWSB (Higgs) mechanism

4 massless vector bosons ($W^+, W^-, Z, \gamma$)

$4 \times 2 + 4$

- 4 DOFs for the Higgs sector
- (Higgs field is a weak isospin doublet)
- 2 transverse modes
- 1 Higgs boson and 3 massless Goldstone bosons
EWSB (Higgs) mechanism

4 massless vector bosons ($W^+, W^-, Z, \gamma$)

$4 \times 2 + 4$

2 transverse modes

4 DOFs for the Higgs sector
(Higgs field is a weak isospin doublet)

1 Higgs boson and 3 massless Goldstone bosons

3 massive bosons ($W^+, W^-, Z$)

$3 \times 3 + 2 + 1$

Massless $\gamma$ the Higgs boson

2 transverse modes +

1 longitudinal mode

- Important to test EWSB by studying the scattering of longitudinal modes of massive vector bosons (longitudinal vector boson scattering): $V_L V_L \rightarrow V_L V_L$
Fermion masses

- Masses of other matter particles (Fermions) come from the Yukawa coupling between the particle and the Higgs field.
- The coupling depends on the mass of the particle, Higgs likes to couple to heavy particles ($\kappa_{Htt} \gg \kappa_{Hee}$)

Empty space is not really empty but filled with the Higgs field
- Matter particles interact with the Higgs field, “slow down” and appear to be massive
Higgs boson discovery in 2012

May 25, 2017

Junjie Zhu - University of Michigan
Seems to be the first fundamental scalar particle

- A very profound discovery, not just a discovery of another particle
- The Higgs discovery to particle physics is like the DNA discovery to biology
- A scalar particle lacks of internal structure and is thus easier to deal with, however many people argue about its actual existence in nature
- Non-zero spin particles remain massless or light due to symmetries on their extra structure
- Spin-0 particle masses are unprotected against large quantum corrections
  \[ \Delta m_H^2 \propto \Lambda^2 \text{ with } \Lambda \sim 10^{19} \text{ GeV} \]
- Fine tuning problem (measured \( m_H = 125 \text{ GeV} \)) \( \rightarrow \) SUSY or other theories
Higgsaw puzzle
Higgsaw puzzle

- Does it couple to particle masses?
- Will it decay to other final states not predicted by the SM?
- Does it have other neutral or charged siblings?
- What is its spin?
- Is it a scalar particle?
- Is it an elementary or composite particle?
- Why its mass is around 125 GeV?
- Is it the first SUSY particle ever observed?
- ...
Longitudinal Vector Boson Scattering ($V_L V_L \rightarrow V_L V_L$)

The discovery of a Higgs boson does not totally validate the Higgs mechanism, a few other theories also predict the existence of a Higgs boson.

Higgs mechanism: the Goldstone bosons after the EWSB are “eaten” by massless W/Z bosons and become their longitudinal modes.

Need to observe $V V \rightarrow V V$ first and then study $V_L V_L \rightarrow V_L V_L$.

$V_1 V_2 \rightarrow V_1 V_2$ ($V_1, V_2 = W, Z$) scattering

arXiv:1412.8367
VBS-EWK processes

VBS processes

No QCD vertices involved

Non-scattering EWK processes
VBS processes are interesting processes to study.
Investigate different selection criteria (forward jets, large $m_{jj}$, $\Delta y_{jj}$, central-jet veto etc) to reduce the contributions from QCD production and non-scattering EWK production.
EWK vs QCD cross sections

- Not an easy task to observe VBS:
  - We do not have W/Z beams
  - Large reducible and irreducible SM backgrounds
  - Often could not fully reconstruct the final states W and/or Z bosons
- EWK and QCD production by channel
  - **After some analysis cuts to reduce QCD production**
  - $W^±W^±$ has no gluon initial states
- Others experimentally challenging
First study of $W^\pm W^\pm \rightarrow W^\pm W^\pm$

$m_{jj} = 2800$ GeV \hspace{1cm} |\Delta y_{jj}| = 6.3

Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC
Event selection

- Exactly two SS isolated leptons with $p_T > 25$ GeV and $|\eta| < 2.5$
- MET > 40 GeV
- At least two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
- **WZ veto**: veto a third lepton with lower $p_T$ and looser quality requirements
- **Z veto**: $|m_{ee} - m_Z| > 10$ GeV to suppress the $Z \rightarrow ee$ contribution with the charge of one electron misidentified
- **ttbar veto**: no b-tagged jets in each event
- Inclusive region: $m_{jj} > 500$ GeV
- VBS region: $m_{jj} > 500$ GeV and $|\Delta y_{jj}| > 2.4$ \(\rightarrow\) enhance the contribution from electroweak production
Inclusive and VBS signal regions

Lepton centrality: 
\[ \zeta = \min\{\eta(j_1) - \eta(l_1), \eta(l_2) - \eta(j_2)\} \]
where \( \eta(j_1) > \eta(j_2) \) and \( \eta(l_1) > \eta(l_2) \)
## Signal region numbers

### Inclusive Signal Region

<table>
<thead>
<tr>
<th></th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\pm jj$ Electroweak</td>
<td>3.07 ± 0.30</td>
<td>9.0 ± 0.8</td>
<td>4.9 ± 0.5</td>
<td>16.9 ± 1.5</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Strong</td>
<td>0.89 ± 0.15</td>
<td>2.5 ± 0.4</td>
<td>1.42 ± 0.23</td>
<td>4.8 ± 0.8</td>
</tr>
<tr>
<td>$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$</td>
<td>3.0 ± 0.7</td>
<td>6.1 ± 1.3</td>
<td>2.6 ± 0.6</td>
<td>11.6 ± 2.5</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>1.1 ± 0.6</td>
<td>1.6 ± 0.8</td>
<td>–</td>
<td>2.7 ± 1.2</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>2.1 ± 0.4</td>
<td>0.77 ± 0.27</td>
<td>–</td>
<td>2.8 ± 0.6</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>0.61 ± 0.30</td>
<td>1.9 ± 0.8</td>
<td>0.41 ± 0.22</td>
<td>2.9 ± 0.8</td>
</tr>
<tr>
<td>Total Predicted</td>
<td>10.7 ± 1.4</td>
<td>21.7 ± 2.6</td>
<td>9.3 ± 1.0</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>Data</td>
<td>12</td>
<td>26</td>
<td>12</td>
<td>50</td>
</tr>
</tbody>
</table>

### VBS Signal Region

<table>
<thead>
<tr>
<th></th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\pm jj$ Electroweak</td>
<td>2.55 ± 0.25</td>
<td>7.3 ± 0.6</td>
<td>4.0 ± 0.4</td>
<td>13.9 ± 1.2</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Strong</td>
<td>0.25 ± 0.06</td>
<td>0.71 ± 0.14</td>
<td>0.38 ± 0.08</td>
<td>1.34 ± 0.26</td>
</tr>
<tr>
<td>$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$</td>
<td>2.2 ± 0.5</td>
<td>4.2 ± 1.0</td>
<td>1.9 ± 0.5</td>
<td>8.2 ± 1.9</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>0.7 ± 0.4</td>
<td>1.3 ± 0.7</td>
<td>–</td>
<td>2.0 ± 1.0</td>
</tr>
<tr>
<td>OS prompt leptons</td>
<td>1.39 ± 0.27</td>
<td>0.64 ± 0.24</td>
<td>–</td>
<td>2.0 ± 0.5</td>
</tr>
<tr>
<td>Other non-prompt</td>
<td>0.50 ± 0.26</td>
<td>1.5 ± 0.6</td>
<td>0.34 ± 0.19</td>
<td>2.3 ± 0.7</td>
</tr>
<tr>
<td>Total Predicted</td>
<td>7.6 ± 1.0</td>
<td>15.6 ± 2.0</td>
<td>6.6 ± 0.8</td>
<td>29.8 ± 3.5</td>
</tr>
<tr>
<td>Data</td>
<td>6</td>
<td>18</td>
<td>10</td>
<td>34</td>
</tr>
</tbody>
</table>
Cross section extraction

- Profile likelihood ratio method used to extract the final cross sections from all three channels taken into account correlated systematics

\[ L(\sigma_{W^\pm W^\pm jj}, \mathcal{L}, \alpha_j) = \text{Gaus}(\mathcal{L}_0 | \mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i \in \{ee, \mu\mu, e\mu\}} \text{Pois}(N^{\text{obs}}_{i} | N^{\text{exp}}_{i, \text{tot}}) \prod_{j \in \text{syst}} \text{Gaus}(\alpha_j^0 | \alpha_j, 1) \]

- Inclusive SR: \( \sigma = 2.1 \pm 0.5 \) (stat) \( \pm 0.3 \) (syst) fb, 4.5\( \sigma \) obs. (3.4\( \sigma \) exp.)
- VBS SR: \( \sigma = 1.3 \pm 0.4 \) (stat) \( \pm 0.2 \) (syst) fb, 3.6\( \sigma \) obs. (2.8\( \sigma \) exp.)

- First evidence for EWK VV \( \rightarrow \) VV scattering at the LHC

PRL 113, 141803 (2014)
PRL Editor’s Suggestion
CMS 13 TeV results

CMS Preliminary

35.9 fb⁻¹ (13 TeV)

Events

35.9 fb⁻¹ (13 TeV)

Events

m_{jj} [GeV]

m_{ll} [GeV]
Transversal vs longitudinal scattering

$W^+ W^+ \rightarrow W^+ W^+$

$\sigma$ (pb)

$W_T W_T + W_T W_L$

$W_L W_L$ no Higgs

$W_L W_L M_H = 1$ TeV

$W_L W_L M_H = 500$ GeV

$W_L W_L M_H = 120$ GeV

$E_{cm}$ (GeV)

$\ln \eta < 1.5$

arXiv:1412.8367
Angular distribution

Cannot directly measure $\theta^*$ in the dileptonic channel due to the presence of missing transverse energy.

People developed some non-$\theta^*$ variables such as $\Delta\phi_\parallel$ or $p_{T_{11}}/p_{T_{j1}} \times p_{T_{l2}}/p_{T_{j2}}$ to extract the longitudinal fractions, no golden variables found yet.
Machine learning neural network

- Really common in HEP to use multivariate techniques classification (discret estimation)
- Just a simple $f(x_i) \rightarrow \text{Output}$
- Train weights so this mapping gives you the best discriminate between signal and background

![Diagram showing a neural network model with event inputs, hidden layers, and signalness output, with a softmax function equation: $\sigma(z_j) = \frac{e^{z_j}}{\sum_{k=1}^{K} e^{z_k}}$.](image-url)
Machine learning neural network

- You can also train NN to approximate continuous functions (Regression)
- Not squash the outputs

My favorite truth value

My other favorite truth value

Event Inputs Hidden Layers Outputs
Training the neural network

- Deep learning is simply extending a simple neural network with many layers
  - Conceptually simple, computationally difficult
- Use Deep Learning to get a good approximate of the true $\cos(\theta^*)$
  - Network with 20 layers and 200 nodes
  - Validated on independent data
Each event has two W bosons so we make templates based on the Neural Network output:
- Events with 2 Longitudinal bosons
- Events with 1 Longitudinal bosons
- Events with 0 Longitudinal bosons
Neural network fit

- 6 templates
  - ++, --, +-, LL, +L, -L
- Combined into three templates: TT, TL and LL
- **This plot is made assuming a perfect detector**
  - In the least optimistic case with non-optimized cuts, and no detector upgrades we expect a measurement of the LL fraction of about $7^{+6}_{-5}\%$

![Graph showing events for 1 ab$^{-1}$](image)

*Phys Rev D 93 094033 (2016)*
New resonances in $V_L V_L \rightarrow V_L V_L$

Without a SM Higgs boson, Unitarity violation

With a SM Higgs boson, Unitarity is restored

- The Higgs boson is the most economical solution to restore the unitarity, but it is not the only choice (new particle + (non)-SM Higgs)
W$^+W^-jj$ resonance search

- Search for neutral heavy resonances in the W$^+W^-jj$ channel

- Whizard is used to generate new resonances
  - Assume that new resonances only couples to the longitudinal component of the W boson
  - K-matrix unitarization is used
  - Coupling constant $g=2.5$ is used

<table>
<thead>
<tr>
<th>Type</th>
<th>Spin $J$</th>
<th>Isospin $I$</th>
<th>Electric Charge</th>
<th>$\Gamma/\Gamma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar isoscalar</td>
<td>$\sigma$</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Scalar isotensor</td>
<td>$\phi$</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Vector isovector</td>
<td>$\rho$</td>
<td>1</td>
<td>1</td>
<td>$-\frac{4}{3}\left(\frac{v^2}{m^2}\right)$</td>
</tr>
<tr>
<td>Tensor isoscalar</td>
<td>$f$</td>
<td>2</td>
<td>0</td>
<td>$\frac{1}{5}$</td>
</tr>
<tr>
<td>Tensor isotensor</td>
<td>$t$</td>
<td>2</td>
<td>2</td>
<td>$\frac{1}{30}$</td>
</tr>
</tbody>
</table>
## Selection criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>event preselection requirements, see text</td>
</tr>
<tr>
<td>2</td>
<td>exactly two leptons with $p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>3</td>
<td>pass single lepton trigger and trigger matching</td>
</tr>
<tr>
<td>4</td>
<td>third lepton veto</td>
</tr>
<tr>
<td>5</td>
<td>dilepton mass $m_{\ell\ell} &gt; 40$ GeV</td>
</tr>
<tr>
<td>6</td>
<td>$q_{\ell_1} \times q_{\ell_2} &lt; 0$</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
</tr>
<tr>
<td>8</td>
<td>at least two selected jets with $p_T &gt; 30$ (50) GeV and $</td>
</tr>
<tr>
<td>9</td>
<td>b-jet veto</td>
</tr>
<tr>
<td>10</td>
<td>$E_T^{\text{miss}} &gt; 35$ GeV</td>
</tr>
<tr>
<td>11</td>
<td>$m_{jj} &gt; 500$ GeV</td>
</tr>
<tr>
<td>12</td>
<td>$</td>
</tr>
<tr>
<td>13</td>
<td>$\eta_{j_1} \times \eta_{j_2} &lt; 0$</td>
</tr>
<tr>
<td>14</td>
<td>lepton centrality $\zeta &gt; -0.5$</td>
</tr>
<tr>
<td>15</td>
<td>$f_{\text{recoil}} &lt; 2.0$</td>
</tr>
</tbody>
</table>
Signal and background contributions in the SR

- Dominant backgrounds from $Z$+jets (for ee and $\mu\mu$ channels) and ttbar (e$\mu$ channel)
- Various control regions defined to validate various background estimates

<table>
<thead>
<tr>
<th></th>
<th>$ee$</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$+jets</td>
<td>17.6 ± 1.2 ± 11.6</td>
<td>36.6 ± 2.3 ± 19.0</td>
<td>6.7 ± 1.2 ± 1.7</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>12.1 ± 0.6 ± 3.2</td>
<td>18.2 ± 0.7 ± 4.6</td>
<td>46.9 ± 1.2 ± 12.1</td>
</tr>
<tr>
<td>$Wt$</td>
<td>1.2 ± 0.2 ± 0.3</td>
<td>1.5 ± 0.2 ± 0.5</td>
<td>3.1 ± 0.3 ± 0.8</td>
</tr>
<tr>
<td>diboson_QCD</td>
<td>3.1 ± 0.3 ± 0.5</td>
<td>4.2 ± 0.3 ± 0.7</td>
<td>10.2 ± 0.3 ± 1.6</td>
</tr>
<tr>
<td>diboson_EW</td>
<td>1.2 ± 0.1 ± 0.1</td>
<td>1.7 ± 0.1 ± 0.2</td>
<td>3.6 ± 0.1 ± 0.4</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>2.1 ± 0.3 ± 0.6</td>
<td>3.8 ± 0.3 ± 0.7</td>
<td>0.1 ± 0.0 ± 0.1</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.3 ± 0.0 ± 0.1</td>
<td>0.4 ± 0.0 ± 0.1</td>
<td>0.8 ± 0.0 ± 0.1</td>
</tr>
<tr>
<td>$ttV$</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>0.1 ± 0.0 ± 0.0</td>
</tr>
<tr>
<td>fake-lepton</td>
<td>0.6 ± 0.6 ± 0.1</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>1.3 ± 0.7 ± 0.1</td>
</tr>
<tr>
<td>$\sigma$ ($m = 300$ GeV)</td>
<td>5.1 ± 0.3 ± 0.6</td>
<td>7.5 ± 0.3 ± 0.9</td>
<td>14.4 ± 0.4 ± 1.9</td>
</tr>
<tr>
<td>$\phi$ ($m = 300$ GeV)</td>
<td>0.3 ± 0.1 ± 0.2</td>
<td>1.0 ± 0.1 ± 0.4</td>
<td>1.6 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td>$\rho$ ($m = 300$ GeV)</td>
<td>8.0 ± 0.4 ± 1.6</td>
<td>11.7 ± 0.4 ± 1.4</td>
<td>24.1 ± 0.6 ± 3.1</td>
</tr>
<tr>
<td>$f$ ($m = 300$ GeV)</td>
<td>15.6 ± 0.6 ± 1.9</td>
<td>22.6 ± 0.8 ± 1.9</td>
<td>50.4 ± 1.2 ± 3.8</td>
</tr>
<tr>
<td>$t$ ($m = 300$ GeV)</td>
<td>3.3 ± 0.2 ± 0.4</td>
<td>4.7 ± 0.2 ± 0.6</td>
<td>6.9 ± 0.3 ± 1.1</td>
</tr>
<tr>
<td>Total background</td>
<td>38.2 ± 1.6 ± 13.9</td>
<td>66.4 ± 2.5 ± 21.6</td>
<td>72.6 ± 1.9 ± 14.8</td>
</tr>
<tr>
<td>Data</td>
<td>40</td>
<td>74</td>
<td>86</td>
</tr>
</tbody>
</table>
VV resonance search
First sets of limits on new resonances

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ \int \text{L} \text{d}t = 3.2 \text{ fb}^{-1} \]

**ATLAS** Preliminary

- Theory $g=2.5$
- Observed Limit
- Expected Limit
- Expected Limit $\pm 1 \sigma$
- Expected Limit $\pm 2 \sigma$

May 25, 2017

Junjie Zh

ATLAS-CONF-2016-053
Anomalous TGCs and QGCs

\[ W_L^+ W_L^+ \rightarrow W_L^+ W_L^+ \text{ with anomalous triple and quartic couplings} \]

\[ W_T^+ W_X^+ \rightarrow W_T^+ W_X^+ \text{ with anomalous triple and quartic couplings} \]
QGC processes

- QGC process: process where a QGC vertex contributes
  - No reaction is ever mediated by a QGC vertex alone
- Two classes of QGC processes are measurable:
  - Vector boson scattering/fusion (VBS/VBF)
  - Triboson production (WWZ as one example)
WWW selection criteria

- Reuse the $l^\pm v l^\pm v j j$ framework we developed for the ssWW analysis
- Later joined by the lvlvlv group

<table>
<thead>
<tr>
<th>$l^\pm v l^\pm v j j$</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>Exactly two same-charge leptons with $p_T &gt; 30$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>At least two jets with $p_T(1) &gt; 30$ GeV, $p_T(2) &gt; 20$ GeV and $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$m_{\ell\ell} &gt; 40$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$E_T^{\text{miss}} &gt; 55$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{jj}$</td>
<td>$65$ GeV $&lt; m_{jj} &lt; 105$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta\eta_{jj}</td>
<td>$</td>
<td>$&lt; 1.5$</td>
</tr>
<tr>
<td>$Z$ boson veto</td>
<td>$m_{ee} &lt; 80$ GeV or $m_{ee} &gt; 100$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third-lepton veto</td>
<td>No third lepton with $p_T &gt; 6$ GeV and $</td>
<td>\eta</td>
<td>&lt; 2.5$ passing looser identification requirements</td>
</tr>
<tr>
<td>$b$-jet veto</td>
<td>No identified $b$-jets with $p_T &gt; 25$ GeV and $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$l^\pm v l^\pm v j j$</th>
<th>0 SFOS</th>
<th>1 SFOS</th>
<th>2 SFOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>Exactly three charged leptons with $p_T &gt; 20$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$E_T^{\text{miss}} &gt; 45$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\phi^M - \phi^{T^{\text{miss}}}</td>
<td>$</td>
<td>$&gt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>m_{ee} - m_{Z}</td>
<td>$</td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td>$m_{Z} - m_{\text{FOS}}$</td>
<td>$&gt; 35$ GeV or $m_{FOS} - m_{Z} &gt; 20$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet veto</td>
<td>At most one jet with $p_T &gt; 25$ GeV and $</td>
<td>\eta</td>
<td>&lt; 4.5$</td>
</tr>
<tr>
<td>$b$-jet veto</td>
<td>No identified $b$-jets with $p_T &gt; 25$ GeV and $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
</tbody>
</table>
Validation regions

<table>
<thead>
<tr>
<th>Validation Region</th>
<th>Signal</th>
<th>Background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>9.78 ± 0.04 ± 0.45</td>
<td>2392 ± 7 ± 298</td>
<td>2472</td>
</tr>
<tr>
<td>Fake-lepton</td>
<td>0.15 ± 0.01 ± 0.02</td>
<td>15 ± 1 ± 10</td>
<td>18</td>
</tr>
<tr>
<td>Zγ</td>
<td>0.32 ± 0.01 ± 0.02</td>
<td>119 ± 3 ± 20</td>
<td>119</td>
</tr>
<tr>
<td>Charge-flip</td>
<td>0.98 ± 0.04 ± 0.06</td>
<td>21 ± 1 ± 2</td>
<td>22</td>
</tr>
<tr>
<td>WZ + 2-jets</td>
<td>0.55 ± 0.03 ± 0.04</td>
<td>52 ± 1 ± 10</td>
<td>56</td>
</tr>
<tr>
<td>b-tagged</td>
<td>1.00 ± 0.05 ± 0.07</td>
<td>69 ± 1 ± 23</td>
<td>78</td>
</tr>
<tr>
<td>W mass sideband</td>
<td>3.35 ± 0.08 ± 0.43</td>
<td>48 ± 2 ± 6</td>
<td>53</td>
</tr>
<tr>
<td>≤ 1 jet</td>
<td>1.62 ± 0.06 ± 0.40</td>
<td>139 ± 3 ± 18</td>
<td>145</td>
</tr>
</tbody>
</table>
## Signal regions ($\ell\ell\nu\nu\nu$)

<table>
<thead>
<tr>
<th>$\ell\ell\nu\nu\nu$</th>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm \mu^\pm$</th>
<th>$\mu^\pm \mu^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\pm W^\pm$ signal</td>
<td>0.46 ± 0.03 ± 0.07</td>
<td>1.35 ± 0.05 ± 0.19</td>
<td>1.65 ± 0.06 ± 0.30</td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.74 ± 0.13 ± 0.44</td>
<td>2.77 ± 0.27 ± 0.66</td>
<td>3.28 ± 0.29 ± 0.71</td>
</tr>
<tr>
<td>Other prompt background</td>
<td>0.46 ± 0.05 ± 0.16</td>
<td>1.33 ± 0.10 ± 0.38</td>
<td>1.33 ± 0.15 ± 0.38</td>
</tr>
<tr>
<td>Charge-flip background</td>
<td>1.13 ± 0.13 ± 0.24</td>
<td>0.74 ± 0.08 ± 0.16</td>
<td>-</td>
</tr>
<tr>
<td>$V\gamma$</td>
<td>0.75 ± 0.35 ± 0.21</td>
<td>2.5 ± 0.7 ± 0.7</td>
<td>-</td>
</tr>
<tr>
<td>Fake-lepton background</td>
<td>0.96 ± 0.15 ± 0.39</td>
<td>2.04 ± 0.22 ± 0.89</td>
<td>0.43 ± 0.06 ± 0.25</td>
</tr>
<tr>
<td>Total background</td>
<td>4.0 ± 0.4 ± 0.7</td>
<td>9.4 ± 0.8 ± 1.4</td>
<td>5.0 ± 0.3 ± 0.8</td>
</tr>
<tr>
<td>Signal + background</td>
<td>4.5 ± 0.4 ± 0.7</td>
<td>10.7 ± 0.8 ± 1.4</td>
<td>6.7 ± 0.3 ± 0.9</td>
</tr>
</tbody>
</table>

Data:

![Graphs showing signal regions for different channels](image)
## Signal regions ($\ell\nu\nu\nu$)

<table>
<thead>
<tr>
<th>$\ell\nu\nu\nu$</th>
<th>0 SFOS</th>
<th>1 SFOS</th>
<th>2 SFOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{\pm}W^{\pm}W^{\mp}$ signal</td>
<td>1.34 ± 0.02 ± 0.07</td>
<td>1.39 ± 0.02 ± 0.08</td>
<td>0.61 ± 0.01 ± 0.03</td>
</tr>
<tr>
<td>WZ</td>
<td>0.59 ± 0.00 ± 0.07</td>
<td>11.9 ± 0.1 ± 1.3</td>
<td>9.1 ± 0.1 ± 1.0</td>
</tr>
<tr>
<td>Other prompt background</td>
<td>0.21 ± 0.01 ± 0.02</td>
<td>0.78 ± 0.02 ± 0.11</td>
<td>0.60 ± 0.02 ± 0.10</td>
</tr>
<tr>
<td>Charge-flip background</td>
<td>0.04 ± 0.00 ± 0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$V\gamma$</td>
<td>-</td>
<td>0.20 ± 0.13 ± 0.29</td>
<td>0.11 ± 0.10 ± 0.29</td>
</tr>
<tr>
<td>Fake-lepton background</td>
<td>1.5 ± 0.3 ± 1.4</td>
<td>1.9 ± 0.3 ± 1.9</td>
<td>0.49 ± 0.16 ± 0.47</td>
</tr>
<tr>
<td>Total background</td>
<td>2.4 ± 0.3 ± 1.4</td>
<td>14.8 ± 0.4 ± 2.3</td>
<td>10.3 ± 0.2 ± 1.2</td>
</tr>
<tr>
<td>Signal + background</td>
<td>3.7 ± 0.3 ± 1.4</td>
<td>16.2 ± 0.4 ± 2.3</td>
<td>10.9 ± 0.2 ± 1.2</td>
</tr>
</tbody>
</table>

| Data | 5 | 13 | 6 |

**ATLAS**

\( \ell s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

\( h\nu\nu\nu \)

- Data
- WWW
- WZ
- Fake L.
- $V\gamma$
- Charge Flip L.
- Other Bkg.

### 0 SFOS SR

### 1 SFOS SR

### 2 SFOS SR

---

**May 25, 2017**

Junjie Zhu - University of Michigan
Cross section results

- Cross sections determined using events from all six channels
- Cross sections for both fiducial and common regions are determined

<table>
<thead>
<tr>
<th></th>
<th>Fiducial $\ell\nu\ell\nu$</th>
<th></th>
<th>Fiducial $\ell\nu\ell\nu$</th>
<th></th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.309 \pm 0.007$ (stat.)</td>
<td>$\pm 0.015$ (PDF) $\pm 0.008$ (scale)</td>
<td>$0.31^{+0.35}<em>{-0.33}$ (stat.) $^{+0.32}</em>{-0.35}$ (syst.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.286 \pm 0.006$ (stat.)</td>
<td>$\pm 0.015$ (PDF) $\pm 0.010$ (scale)</td>
<td>$0.24^{+0.39}<em>{-0.33}$ (stat.) $^{+0.19}</em>{-0.19}$ (syst.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$241.5 \pm 0.1$ (stat.)</td>
<td>$\pm 10.3$ (PDF) $\pm 6.3$ (scale)</td>
<td>$230 \pm 200$ (stat.) $^{+150}_{-160}$ (syst.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Graph] $-2 \log \lambda$ vs. Total Cross Section [fb]

ATLAS

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

$W^+W^-W^+ \rightarrow \ell\nu\ell\nu + \ell\nu\ell\nu$

- Obs. (Sys+Stat)
- Exp. (Sys+Stat)
- Exp. (Stat Only)

Observed: 230 fb

Expected fb
The distribution of $m_T^2$ for the $t\bar{t}l\ell\nu$ channel (left) and the distribution of $\Sigma p_T$ for the $t\bar{t}lj$ channel (right) as observed in the data (dots with error bars indicating the statistical uncertainties) and as expected from SM signal and background processes. The ratios between the observed numbers of events in data and the expected SM signal plus background contributions are shown in the lower panels. The hashed bands result from the systematic uncertainties on the sum of the signal plus background contributions. The "other backgrounds" contain prompt leptons and are estimated from MC.

From the ATLAS Collaboration: Search for triboson $W^+W^+W^+$ production in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.
Anomalous QGCs

- Often how we describe sensitivity to new physics
  - Allow for new operators in the Lagrangian typically dimension 8 for aQGC
  - Generally produces production enhancements at high boson $p_T$

- ATLAS has been using the $\alpha_4, \alpha_5$ parameterization

- Moving toward $f_{s0}, f_{s1}$ parameterization

\[
\mathcal{L}_{4} = \alpha_4 (\text{tr} [V_\mu V_\nu])^2 \\
\mathcal{L}_{5} = \alpha_5 (\text{tr} [V_\mu V_\mu])^2
\]

- If parameters become large these models become unphysical (are un-unitarized)
  - ATLAS addresses this with a K-Matrix of form factor
**aQGCs from $W^\pm W^\pm jj$ scattering**

- Cuts on the transverse mass of the WW system can enhance aQGC sensitivity

**ATLAS**

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

VBS SR, $e\bar{e}+e\mu+\mu\mu$

- Data

- Syst. Uncertainty

- $\alpha_4 = 0.1$, $\alpha_5 = 0$

- $W^3W^3jj$ EW

- $W^3W^3jj$ QCD

- Prompt

- Conversions

- Non-prompt

---

**ATLAS** Preliminary

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

$pp \rightarrow W^\pm W^\pm jj$

K-matrix unitarization

---

Confidence regions

- 68% CL

- 95% CL

- expected 95% CL

- expected 95% CL PRL 113, 141803

---

arXiv: 1611.02428

Submitted to Phys. Rev. D
aQGCs from WWW

- Use the observed cross sections to set limits on $f_{s,0}$, $f_{s,1}$

---

Confidence Intervals
- 95% CL
- 68% CL
- Observed 95% CL
- Observed Value

**ATLAS**
- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- $W^+W^-W^+ \rightarrow l\nu\bar{\nu}j+l\nu\nu\nu$
- $\Lambda_{FF} = 1$ TeV

**Confidence Intervals**
- 95% CL
- 68% CL
- Observed 95% CL
- Observed Value

**ATLAS**
- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- $W^+W^-W^+ \rightarrow l\nu\bar{\nu}j+l\nu\nu\nu$
- $\Lambda_{FF} = \infty$

---

**Unitarized**

**Un-unitarized**

EPJC (2017) 77, 141
Conclusions

- The Higgs mechanism was introduced to explain the EWSB and origin of mass for elementary particles
- Important to study VBS processes to obtain a better understanding of the EWSB (need to know if this boson is fully or only partially responsible for the EWSB in the whole energy regime, determine the dynamics of EWSB)
- A few topics shown with significant contributions from my group:
  - First evidence for $W^\pm W^\pm j j$ VBS process
  - Use deep machine learning technique to extract longitudinal fractions
  - First search for neutral resonances in the $W^+W^-jj$ channel
  - First search for the WWW process
  - Limits on aQGCs from both $W^\pm W^\pm j j$ and WWW processes
- More studies with 13/14 TeV data ongoing