Vector Boson Scattering in Semi-leptonic Final States with the ATLAS Detector

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Lepton Photon 2019
Semi-leptonic Vector Boson Scattering (VBS)

Search in the “semi-leptonic” VBS channel
- one hadronic $V$ decay:
  - One or two energetic jets
- one leptonic $V$ decay:
  - $\ell\bar{\ell}$, $\ell + E_{T,\text{miss}}$, or large $E_{T,\text{miss}}$
  - Two forward jets which identify the topology

Compromise between competing effects:
- Hadronic decays $\implies$ high BR
- Leptonic decays $\implies$ less backgrounds

<table>
<thead>
<tr>
<th>$\ell = e, \mu, \nu$</th>
<th>$WW$</th>
<th>$WZ$</th>
<th>$ZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\ell\ell\ell$</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
</tr>
<tr>
<td>$\ell\ell q\bar{q}$</td>
<td>30%</td>
<td>33%</td>
<td>36%</td>
</tr>
<tr>
<td>$q\bar{q}q\bar{q}$</td>
<td>45%</td>
<td>46%</td>
<td>48%</td>
</tr>
<tr>
<td>other</td>
<td>20%</td>
<td>15%</td>
<td>9%</td>
</tr>
</tbody>
</table>
The opening angle:
\[ \Delta R \approx 2 \frac{m(V)}{p_T(V)} \]

To reduce backgrounds can design a V-tagger:
- Mass of the large-R jet
- \( D_2^{\beta=1} \) sub-structure variable

Trained a Boosted Decision Tree to optimize search significance in each region.
Signal strength:
\[ \mu = 1.05^{+0.42}_{-0.40} = 1.05 \pm 0.2 \text{(stat)}^{+0.37}_{-0.34} \text{(syst)} \]

Signal significance:
2.7\(\sigma\) observed (2.5\(\sigma\) expected)

Fiducial cross-sections measurements also provided

<table>
<thead>
<tr>
<th>Fiducial phase space</th>
<th>Predicted (\sigma_{\text{EW, VVjj}}^{\text{fid,SM}}) [fb]</th>
<th>Measured (\sigma_{\text{EW, VVjj}}^{\text{fid,obs}}) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merged</td>
<td>11.4 ± 0.7 (theo.)</td>
<td>12.7 ± 3.8 (stat.)^{+4.8}_{-4.2} (syst.)</td>
</tr>
<tr>
<td>Resolved</td>
<td>31.6 ± 1.8 (theo.)</td>
<td>26.5 ± 8.2 (stat.)^{+17.4}_{-17.1} (syst.)</td>
</tr>
<tr>
<td>Inclusive</td>
<td>43.0 ± 2.4 (theo.)</td>
<td>45.1 ± 8.6 (stat.)^{+15.9}_{-14.6} (syst.)</td>
</tr>
</tbody>
</table>
Future Prospects

- Uncertainties can be reduced with further statistics and improved modeling
- At the HL-LHC expect precision at the percent level cross-section measurement

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\sigma_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
<td>0.41</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.20</td>
</tr>
<tr>
<td>Systematic</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Theoretical and modeling uncertainties

- Floating normalizations: 0.09
- $Z + \text{jets}$: 0.13
- $W + \text{jets}$: 0.09
- $t\bar{t}$: 0.06
- Diboson: 0.09
- Multijet: 0.04
- Signal: 0.07
- MC statistics: 0.17

Experimental uncertainties

- Large-$R$ jets: 0.08
- Small-$R$ jets: 0.06
- Leptons: 0.02
- $E_T^{\text{miss}}$: 0.04
- $b$-tagging: 0.07
- Pileup: 0.04
- Luminosity: 0.03
Vector Boson Scattering is an interesting process which probes the gauge and Higgs structure of the SM:

- Leptonic channels provide cleanest signal
- Semi-leptonic channels probe the tails

Semi-leptonic search utilize modern techniques

- Boosted jet topologies and jet substructure
- Boosted Decision Trees to provide strong discriminants

Future Prospects:

- With full 2015-2018 ATLAS data expect $5\sigma$ observation
- Effective Field Theory Interpretations
- In HL-LHC era expect percent level measurements