Measurements of Vector Boson Fusion with the ATLAS detector

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EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017
Electroweak ("EW") $Wjj$ production measurement at 7 and 8 TeV

- Submitted to EPJC – available on [arXiv](https://arxiv.org)
- Observation of electroweak $W$-boson production in the VBF topology
- Fiducial and (for the first time) differential measurements
  - Focus on variables sensitive to kinematic differences of QCD and EW $Wjj$ production
- TGC vertex is a probe for new physics beyond the Standard Model
  - Limits on anomalous TGC are set using an aTGC or EFT framework

EW $Zjj$ production measurement at 13 TeV (3.2 fb$^{-1}$, 2015 data)

- Available on arXiv imminently
- Fiducial cross sections measured in regions enriched with EW $Zjj$
- Inclusive cross section measured in six fiducial regions with varying contributions from QCD and EW production
**Wjj – Motivation**

### Electroweak $Wjj$ production (Signal)

- **TGC**
- **Vector boson fusion**
- **Bremsstrahlung-like**
- **non-resonant**

- $W$: Lepton and $E_{T\text{miss}}$ from neutrino
- Two high-$p_T$ jets with large invariant mass $M_{JJ}$
- EW production:
  - $W$ boson inside the rapidity range of two jets
  - No additional jets in the rapidity range between jets (absence of color connection between incoming partons)
- QCD “background”:
  - $M_{JJ}$ typically lower than in EW production
  - $W$ boson can be outside the rapidity “gap” of leading jets
  - Additional jet radiation allowed inside rapidity gap between leading jets

### Strong (QCD) $Wjj$ production (Background)
Wjj Event Selection, Definition of Fiducial Regions

- **Basic Wjj (W→ℓν) selection:**
  - 1 triggered lepton ($p_T > 25$ GeV)
  - $E_{T\text{miss}} > 20$ GeV, $M_T(ℓ,E_{T\text{miss}}) > 40$ GeV
  - 2 high-$p_T$ jets with $M_{JJ} > 500$ GeV

- **Discriminate EW from QCD Wjj using Jet and Lepton centrality:**
  - 1 lepton inside the *dijet rapidity gap*
  - No additional jets inside the rapidity gap

- **Control / validation regions defined using lepton and jet centrality**
  - Constrain QCD Wjj using *forward lepton control* region (0 central leptons or jets)
  - Validation region with $\geq 1$ central jet, 1 central lepton

\[
C_ℓ (j) ≜ \left| \frac{y_ℓ (j) - \frac{y_1 + y_2}{2}}{y_1 - y_2} \right|
\]

\[\text{Central region}\]

\[+0.4\]

\[+0.5\]

\[-0.5\]

\[-0.4\]

Jet 1

Jet 2

**Inclusive**

**Forward-lepton/central-jet region**
- $N_{\text{jets}} \geq 1$
- $N_{\text{lepton}} = 0$

**Forward-lepton control region**
- $N_{\text{jets}} = 0$
- $N_{\text{lepton}} = 0$

**Central-jet validation region**
- $N_{\text{jets}} \geq 1$
- $N_{\text{lepton}} = 1$

**Signal region**
- $N_{\text{jets}} = 0$
- $N_{\text{lepton}} = 1$
QCD- and EW-$Wjj$ fractions are obtained using fit to the $M_{jj}$ spectrum with MC

- QCD MC suffers from mismodeling in $M_{jj}$ spectrum; constrained using forward lepton control region

Other backgrounds:
- Multijet production, constrained using data-driven techniques
- Top quarks, $Zjj$, dibosons (modeled using MC)
Fiducial Measurement Results

**Measured EW $Wjj$ production ($M_{jj}>0.5$ TeV)**

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\sigma_{\text{meas}}^{\text{fid}}$ [fb]</th>
<th>$\sigma_{\text{SM}}^{\text{fid}}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>144 ± 23 (stat) ± 23 (exp) ± 13 (th)</td>
<td>144 ± 11</td>
</tr>
<tr>
<td>8 TeV</td>
<td>159 ± 10 (stat) ± 17 (exp) ± 20 (th)</td>
<td>198 ± 12</td>
</tr>
</tbody>
</table>

ATLAS

LHC electroweak Xjj production measurements

ATLAS EW $Wjj$ $\sqrt{s}=7$ TeV
This paper (CERN-EP-2017-008)

ATLAS EW $Wjj$ $\sqrt{s}=8$ TeV
This paper (CERN-EP-2017-008)

- EW $Wjj$ production measured at 7 and 8 TeV in the signal region ($M_{jj}>0.5$ TeV)
  - 24% uncertainty in 7 TeV measurement
  - 18% uncertainty in 8 TeV measurement
- QCD+EW $Wjj$ measured in inclusive regions (no $C_j$ or $C_\ell$ requirements) and control regions
Differential Cross Section Measurements

- Differential measurements are made for **QCD+EW Wjj** (in inclusive signal regions) as well as **EW-only Wjj** in high-\(M_{jj}\) regions
  - For EW-only differential definitions, QCD normalization factor measured earlier
- Focus on differential distributions that discriminate between QCD and EW Wjj production
  - \(M_{jj}, C_J, C_e, \Delta y(j_1,j_2), N_{j,gap}\)
- Also differential distributions with sensitivity to anomalous TGCs
  - \(p_{Tj_1}, p_{Tj_2}, \Delta\phi(j_1,j_2)\)
Limits on aTGC

<table>
<thead>
<tr>
<th>$\Lambda = 4$ TeV</th>
<th>$\Lambda = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected</strong></td>
<td><strong>Observed</strong></td>
</tr>
<tr>
<td>$\Delta g_1^Z$</td>
<td>$[-0.39, 0.35]$</td>
</tr>
<tr>
<td>$\Delta \kappa Z$</td>
<td>$[-0.38, 0.51]$</td>
</tr>
<tr>
<td>$\lambda_V$</td>
<td>$[-0.16, 0.12]$</td>
</tr>
<tr>
<td>$\tilde{\kappa}_Z$</td>
<td>$[-1.7, 1.8]$</td>
</tr>
<tr>
<td>$\tilde{\lambda}_V$</td>
<td>$[-0.13, 0.15]$</td>
</tr>
</tbody>
</table>

- Anomalous coupling measurements performed in high-$q^2$ region
  - $M_{JJ} > 1$ TeV, $p_{T,j1} > 600$ GeV
- Sensitive differential variables:
  - $p_{T,j1}$, $p_{T,jj}$, $\Delta \varphi(j_1,j_2)$ (CP-violating couplings)
- Limits placed on aTGC effective Lagrangian couplings, as well as on EFT parameters

Theoretical predictions with aTGC parameters set to +10% from SM predictions
- Measurement at 13 TeV using 3.2 fb\(^{-1}\) of data collected in 2015
- QCD+EW Zjj production measured in 4 fiducial regions
- EW-only Zjj production measured in 2 regions designed to enhance EW signal:
  - High dijet \(M_{\text{jj}}\) (either \(M_{\text{jj}} > 250\) GeV or \(M_{\text{jj}} > 1\) TeV)
  - A central jet veto to suppress QCD production
- EW-only measurement: Fit EW and QCD Zjj components in the \(M_{\text{jj}}\) distribution
Signal Selection

**ATLAS Preliminary**

- Events / GeV
- Data
- EW-Zjj (POWHEG)
- QCD-Zjj (SHERPA 2.2)
- Diboson
- Top quark
- Data Stat. ⊕ MC Syst.

**QCD-enriched**
- 2 same-flavor leptons; $m_{\ell\ell}$ required to be within 10 GeV of PDG Z mass
- “Baseline jets” require $|y| < 4.4$, $p_{Tj_1} > 55$ GeV, $p_{Tj_2} > 45$ GeV
  - Other fiducial regions have higher $p_T$ thresholds
- Balance of object momenta: $p_T^{\text{balance}} < 0.15$
  - Reduces backgrounds with jets from pile-up or multiple interactions
- EW Zjj regions: Central Jet Veto
  - No jet ($p_T > 25$ GeV) in the rapidity region bounded by 2 leading jets
  - A QCD-enriched region requiring $\geq 1$ jet in this region is used to correct the QCD component

\[ p_T^{\text{balance}} = \frac{|\vec{p}_T^{j_1}| + |\vec{p}_T^{j_2}| + |\vec{p}_T^{j_1} + \vec{p}_T^{j_2}|}{|\vec{p}_T^{j_1}| + |\vec{p}_T^{j_2}|} \]
Constraining QCD with a data-driven approach

QCD Mismodeling in EW-enriched region

- QCD modeling of $M_{JJ}$ is imperfect in EW-enriched region and QCD-enriched control region
- Use QCD-enriched control region to derive a linear data-MC $M_{JJ}$ correction factor
- Resulting corrected QCD $M_{JJ}$ distribution is used in fit to determine EW $Zjj$
Corrected QCD $Zjj$ distribution is normalized via a log-likelihood fit of QCD and EW $Zjj$ simulation in the $M_{jj}$ distribution.

EW $Zjj$ fiducial cross section is calculated using:

$$\sigma_{EW}^f = \frac{N_{ob}^f - N_{QCD-Zjj}^f - N_{bkg}^f}{L \cdot C_{EW}^f}$$

...with other backgrounds subtracted using simulation predictions, and a correction factor $C_{EW}^f$ to correct for detector-level efficiency and resolution effects ($L$ is luminosity).
Results – $Zjj$

- Results of QCD+EW $Zjj$ fiducial measurements compared to leading MC predictions in all 6 fiducial regions
- EW-only $Zjj$ cross sections measured in 2 enriched fiducial regions
  - Compatible with SM predictions
- EW production increase vs c.o.m. energy well-predicted by MC

<table>
<thead>
<tr>
<th>EW-enriched Fiducial Region</th>
<th>$\sigma_{Zjj}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{jj} &gt; 250$ GeV</td>
<td>119 ± 16 ± 20 ± 2</td>
</tr>
<tr>
<td>$m_{jj} &gt; 1$ TeV</td>
<td>34.2 ± 5.8 ± 5.5 ± 0.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{jj} &gt; 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
</tr>
<tr>
<td>34.2 ± 5.8 ± 5.5 ± 0.7</td>
</tr>
</tbody>
</table>
Summary and Conclusions

LHC electroweak $Xjj$ production measurements

- **Preliminary $Zjj$ 13 TeV ATLAS results**

- $Wjj$ results at 7 and 8 TeV with small relative uncertainties
  - First differential cross section measurements of EW $Wjj$ production
- Preliminary $Zjj$ result begins the process of extending Electroweak production physics to higher-energy regimes
## Zjj Fiducial Region Descriptions

<table>
<thead>
<tr>
<th>Object</th>
<th>Baseline</th>
<th>High-mass</th>
<th>High-$p_T$</th>
<th>EW-enriched</th>
<th>EW-enriched, $m_{jj} &gt; 1$ TeV</th>
<th>QCD-enriched</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
<td></td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.47, \ p_T &gt; 25$ GeV, $\Delta R_{j, \ell} &gt; 0.4$</td>
</tr>
<tr>
<td>Dilepton pair</td>
<td></td>
<td></td>
<td></td>
<td>$81 &lt; m_{\ell\ell} &lt; 101$ GeV</td>
<td>$p_T^{\ell\ell} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td></td>
<td></td>
<td></td>
<td>$</td>
<td>y</td>
<td>&lt; 4.4$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{j_1} &gt; 55$ GeV</td>
<td>$p_T^{j_1} &gt; 85$ GeV</td>
<td>$p_T^{j_1} &gt; 55$ GeV</td>
<td>$p_T^{j_2} &gt; 45$ GeV</td>
<td>$p_T^{j_2} &gt; 75$ GeV</td>
<td>$p_T^{j_2} &gt; 45$ GeV</td>
</tr>
<tr>
<td>Dijet system</td>
<td>—</td>
<td>$m_{jj} &gt; 1$ TeV</td>
<td>—</td>
<td>$m_{jj} &gt; 250$ GeV</td>
<td>$m_{jj} &gt; 1$ TeV</td>
<td>$m_{jj} &gt; 250$ GeV</td>
</tr>
<tr>
<td>Interval jets</td>
<td>—</td>
<td>—</td>
<td>0</td>
<td>$N_{\text{interval jet (}p_T&gt;25\text{ GeV)} = 0}$</td>
<td>$N_{\text{interval jet (}p_T&gt;25\text{ GeV)} \geq 1}$</td>
<td></td>
</tr>
<tr>
<td>Zjj system</td>
<td>—</td>
<td>—</td>
<td>$p_T^{\text{balance}} &lt; 0.15$</td>
<td>$p_T^{\text{balance},3} &lt; 0.15$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Expected Composition in fiducial regions

<table>
<thead>
<tr>
<th>Process</th>
<th>Baseline</th>
<th>High-mass</th>
<th>High-$p_T$</th>
<th>EW-enriched</th>
<th>EW-enriched, $m_{jj} &gt; 1$ TeV</th>
<th>QCD-enriched</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD-Zjj</td>
<td>94.2 ± 0.4</td>
<td>86.8 ± 1.6</td>
<td>92.3 ± 0.4</td>
<td>93.4 ± 0.9</td>
<td>72.9 ± 2.1</td>
<td>95.4 ± 0.8</td>
</tr>
<tr>
<td>EW-Zjj</td>
<td>1.5 ± &lt;0.1</td>
<td>10.6 ± 0.2</td>
<td>2.6 ± &lt;0.1</td>
<td>4.8 ± &lt;0.1</td>
<td>26.1 ± 0.5</td>
<td>1.6 ± &lt;0.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>1.6 ± &lt;0.1</td>
<td>1.5 ± 0.1</td>
<td>2.0 ± &lt;0.1</td>
<td>1.0 ± &lt;0.1</td>
<td>0.8 ± 0.1</td>
<td>1.8 ± &lt;0.1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2.6 ± &lt;0.1</td>
<td>1.1 ± 0.1</td>
<td>3.1 ± 0.1</td>
<td>0.7 ± &lt;0.1</td>
<td>0.1 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Single-$t$</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Multijet</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>Total expected</td>
<td>64800</td>
<td>2220</td>
<td>21900</td>
<td>11100</td>
<td>640</td>
<td>7120</td>
</tr>
<tr>
<td></td>
<td>± 130 ± 5220</td>
<td>± 20 ± 200</td>
<td>± 40 ± 1210</td>
<td>± 50 ± 520</td>
<td>± 10 ± 40</td>
<td>± 30 ± 880</td>
</tr>
<tr>
<td>Total observed</td>
<td>67472</td>
<td>1471</td>
<td>22461</td>
<td>11630</td>
<td>490</td>
<td>6453</td>
</tr>
</tbody>
</table>