Measurement of ZZ production with the ATLAS detector and constraints on associated triple gauge couplings

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On behalf of the ATLAS Collaboration
Overview

- Motivation
- Event Selection
- Event Yield and Background
- Fiducial and Total Cross Section Results
- Differential Cross Section Measurements
- Neutral Anomalous Triple Gauge Coupling Limit (nATGC)
- Conclusions
Physics Motivations and Measurements

- Provide a test of the predictions of the electroweak sector of the SM at TeV scale, in particular predictions on the nTGC (absent in SM)
- Probe for new physics by searching deviation from SM
- Anomalous triple gauge couplings, heavy resonances in Z boson pairs...

Physics Motivations

- Provide a test of the predictions of the electroweak sector of the SM at TeV scale, in particular
- Predictions on the nTGC (absent in SM)
- Anomalous triple gauge couplings, heavy resonances in Z boson pairs...

Physics Measurements

Fiducial and total cross section measurements for:

- \( ZZ \rightarrow 4l \), \( ZZ^* \rightarrow 4l \), \( ZZ \rightarrow 2l2\nu \)

Differential cross section and aTGC limits

NNLO gg → ZZ:

- PowHeg

NLO gg → ZZ:

- GG2ZZ MC

\sim 6\%
Fiducial Cross Section ($A_{ZZ} = 1$):

$$\sigma_{ZZ}^{fid} = \frac{N_{obs} - N_{bkg}}{L \cdot C_{ZZ}}$$

Total Cross Section:

($ZZ$ production with $66 < M_Z < 116$ GeV)

$$\sigma_{ZZ}^{total} = \frac{N_{obs} - N_{bkg}}{A_{ZZ} \times C_{ZZ} \times \mathcal{L} \times BF}$$

$C_{ZZ}$: Experimental signal selection acceptance from MC corrected for data-driven measurements of MC mismodeling of detector effects

$A_{ZZ}$: acceptance correction for the phase space region not probed experimentally (MC based)

ZZ production in the experimental phase-space region:
- Defined by lepton $p_T$, $|\eta|$, $\Delta R$, $E_T^{miss}$ coverage
## Measurements Overview

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>ZZ* → 4l</td>
<td></td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>ZZ → ℓνν</td>
<td></td>
<td>✔</td>
<td>✔</td>
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</tbody>
</table>

- Use electrons in the barrel/endcap calorimeter cracks (1.37<|η|<1.52)
- Use electrons with brem-recovery reconstruction
  (~2% higher reconstruction efficiency for high \(E_T\), 6-8% for \(E_T<20\) GeV)
- Use electrons in the Forward Region (2.5<|η|<3.2)
  (No tracking coverage, \(E_T>20\) GeV, 6% gain in event yield)
- Use forward muons (2.5<|η|<2.7, \(p_T>10\) GeV)
  (Outside nominal acceptance of Inner Detector, \(p_T>10\) GeV, 6% gain in event yield)
- Use calorimeter-tagged muons (|η|<0.1, \(p_T>20\) GeV)
  (Limited geometric coverage of muon spectrometer, \(p_T>10\) GeV, 4% gain in event yield)

- Differential cross section for \(p_T^Z\), \(m^{ZZ}\), \(ΔΦ(\ell^+,\ell^-)\)
- Anomalous neutral triple gauge coupling limit
**Event Selection**

\( \text{ZZ}^{(*)} \rightarrow 4\ell \)

- \( P_T > 7 \text{ GeV}, \) isolated
- \( \text{DR}(l_1,l_2) > 0.2 \)
- \( 66 < m_{12} < 116 \text{ GeV} \)
- \( 66 < m_{34} < 116 \text{ GeV} \) [ZZ]
- \( m_{34} > 20 \text{ GeV} \) [ZZ*]

\( \text{ZZ} \rightarrow 2\ell 2\nu \)

- \( P_T > 20 \text{ GeV}, \) isolated
- \( 66 < m_{12} < 116 \text{ GeV} \)
- \( \text{DR}(l_1,l_2) > 0.2 \)
- \( \text{DR}(l,\text{jet}) > 0.3 \)
- \( \text{Jet veto (} P_T > 25 \text{ GeV}) \)
- \( 0.6 < E_T^{\text{miss}} / P_T < 1.4 \)
- \( \text{Axial-}E_T^{\text{miss}} > 75 \text{ GeV} \)
Define lepton-like jets (J):
- Invert isolation, $d_0$ ($\mu$), or PID (e)

Use jets in events with one Z to calculate the efficiency ratio $f(E_T, \eta)$:
- $f(E_T, \eta) \sim (\text{jet} \rightarrow l) / (\text{jet} \rightarrow J)$

Estimate the number of “fake” $N_{4\ell}$ as:

$$N_{4\ell}^{\text{fake}} = N(\ell\ell\ell j) \times f - N(\ell\ell jj) \times f^2 - N_{\text{Correction}}$$

- $WW/WT/t\bar{t}/\tau\tau$ extrapolated from an e- control sample, weighted for BR and ratio of efficiencies $\varepsilon_{ee}$ and $\varepsilon_{e\mu}$
- $WZ$ background if MC estimated validated with a 3 lepton control region
- $Z+\text{jets}$ background estimated with $\gamma+\text{jets}$ data (reweighted by kinematic)

Data Driven Method

**ZZ → 4l Channel**

$Z + j/\gamma + j$

(jj $\rightarrow l\bar{l}$ or $\gamma \rightarrow e, j \rightarrow e$)

Top, diboson, etc.. (small)

**ZZ → 2l2v Channel**

$WW/WT/Top/Z \rightarrow \tau\tau$ ($\sim 41\%$)

$Z+\text{jet}$ (fake $E_T^{\text{miss}}$) ($\sim 44\%$)

$W+\text{jets}$ ($j \rightarrow l$) ($\sim 3\%$)

$WZ$ ($\sim 11\%$)
### Event Yield

#### ZZ(*) → ℓ⁺ℓ⁻ℓ⁺ℓ⁻

<table>
<thead>
<tr>
<th></th>
<th>e⁺e⁻</th>
<th>e⁺−μ⁻−μ⁺μ⁻</th>
<th>e⁺e⁻μ⁺μ⁻</th>
<th>ℓ⁺ℓ⁻ℓ⁺ℓ⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed ZZ</strong></td>
<td>16</td>
<td>23</td>
<td>27</td>
<td>66</td>
</tr>
<tr>
<td><strong>Observed ZZ</strong></td>
<td>21</td>
<td>30</td>
<td>33</td>
<td>84</td>
</tr>
<tr>
<td><strong>Expected ZZ signal</strong></td>
<td>10.3 ± 0.1 ± 1.0</td>
<td>16.5 ± 0.2 ± 0.9</td>
<td>26.7 ± 0.2 ± 1.7</td>
<td>53.4 ± 0.3 ± 3.2</td>
</tr>
<tr>
<td><strong>Expected ZZ signal</strong></td>
<td>12.3 ± 0.2 ± 1.2</td>
<td>20.5 ± 0.2 ± 1.1</td>
<td>31.6 ± 0.3 ± 2.0</td>
<td>64.4 ± 0.4 ± 4.0</td>
</tr>
<tr>
<td><strong>Expected ZZ background</strong></td>
<td>0.5 ± 0.6 ± 0.3</td>
<td>&lt; 0.6</td>
<td>0.7 ± 0.7 ± 0.6</td>
<td>0.9 ± 1.1 ± 0.7</td>
</tr>
<tr>
<td><strong>Expected ZZ background</strong></td>
<td>4.3 ± 1.4 ± 0.6</td>
<td>&lt; 0.9</td>
<td>5.8 ± 1.6 ± 0.9</td>
<td>9.1 ± 2.3 ± 1.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2012</th>
<th>2012</th>
<th>2012</th>
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</thead>
<tbody>
<tr>
<td><strong>Expected ZZ signal</strong></td>
<td>59.5±4.0</td>
<td>90.2±2.7</td>
<td>142.7±5.6</td>
<td>292.5±10.6</td>
</tr>
<tr>
<td><strong>Expected ZZ bkg.</strong></td>
<td>10.0±1.8±1.4</td>
<td>1.1±1.4±0.5</td>
<td>9.3±2.1±3.1</td>
<td>20.4±2.9±5.0</td>
</tr>
</tbody>
</table>

#### ZZ → ℓ⁺ℓ⁻ν̅ν̅

<table>
<thead>
<tr>
<th></th>
<th>e⁺e⁻</th>
<th>μ⁺μ⁻</th>
<th>ℓ⁺ℓ⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed ZZ</strong></td>
<td>35</td>
<td>52</td>
<td>87</td>
</tr>
<tr>
<td><strong>Expected ZZ signal</strong></td>
<td>17.8 ± 0.3 ± 1.7</td>
<td>21.6 ± 0.3 ± 2.0</td>
<td>39.3 ± 0.4 ± 3.7</td>
</tr>
<tr>
<td><strong>Expected ZZ background</strong></td>
<td>20.8 ± 2.3 ± 1.2</td>
<td>26.1 ± 2.8 ± 1.4</td>
<td>46.9 ± 4.8 ± 1.9</td>
</tr>
</tbody>
</table>

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**Event Yield**

**P_T^{ZZ} Distributions**

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**ATLAS**

$\int L \, dt = 4.64 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

Data

<table>
<thead>
<tr>
<th>ZZ → ΓΓΓΓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
</tr>
</tbody>
</table>

**Expected ZZ signal**

---

**ATLAS Preliminary**

$\int L \, dt = 20 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Data

<table>
<thead>
<tr>
<th>ZZ</th>
</tr>
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<tbody>
<tr>
<td>2012</td>
</tr>
</tbody>
</table>

**Expected ZZ signal**
Signal Efficiency and Acceptance

\( C_{ZZ} \): experimental acceptance in fiducial region

\[ C_{ZZ} = \frac{N_{MC \ Pass \ All \ Cuts \ Reconstructed \ ZZ} \times SF}{N_{MC \ Fiducial \ Volume \ Generated \ ZZ}} \]

with \( SF = \frac{\epsilon_{\text{data trig}}}{\epsilon_{\text{MC trig}}} \cdot \frac{\epsilon_{\text{data reco}}}{\epsilon_{\text{MC reco}}} \)

**Systematic Uncertainties on \( C_{ZZ} \) and \( A_{ZZ} \)**

<table>
<thead>
<tr>
<th>Source</th>
<th>2011, 2012 ZZ → ℓ⁺ℓ⁻ℓ⁺ℓ⁻</th>
<th>ZZ* → ℓ⁺ℓ⁻ℓ⁺ℓ⁻</th>
<th>ZZ → ℓ⁺ℓ⁻νννv</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{ZZ} )</td>
<td>3.0% 2.8% 3.1%</td>
<td>1.6%</td>
<td>1.5% 0.8% 1.0%</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton energy/momentum</td>
<td>0.2% 0.1% 0.3%</td>
<td>1.9%</td>
<td>1.6% 1.5%</td>
</tr>
<tr>
<td>Lepton isolation and impact parameter</td>
<td>1.9% 1.6% 2.0%</td>
<td>0.6% 0.8%</td>
<td></td>
</tr>
<tr>
<td>Jet+( E_T^{\text{miss}} ) modelling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet veto</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.2% 0.1% 0.2%</td>
<td>1.6%</td>
<td>1.5% 0.8% 1.0%</td>
</tr>
<tr>
<td>PDF and scale</td>
<td>1.6% 1.5% 1.5%</td>
<td>1.6%</td>
<td>1.5% 0.8% 1.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( A_{ZZ} )</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet veto</td>
<td>—</td>
<td>—</td>
<td>2.3%</td>
</tr>
<tr>
<td>PDF and scale</td>
<td>0.6% 1.0%</td>
<td>—</td>
<td>1.9%</td>
</tr>
<tr>
<td>Generator modelling and parton shower</td>
<td>1.1% 0.8%</td>
<td>—</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

**Selection**

\| Selection | 2011, 2012 | \( C_{ZZ} \) | \( A_{ZZ} \) |
<table>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( ZZ \to ℓ⁺ℓ⁻ℓ⁺ℓ⁻ )</td>
<td>0.552 ± 0.002 ± 0.021</td>
<td>0.804 ± 0.001 ± 0.010</td>
<td>0.68 ± 0.02</td>
</tr>
<tr>
<td>( ZZ \to ℓ⁺ℓ⁻νννv )</td>
<td>0.679 ± 0.004 ± 0.014</td>
<td>0.64 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>
Cross Section Measurements and Comparison with Theory

Total Cross Sections:

\[ \sigma_{ZZ}^{tot}(8 \text{ TeV}) = 7.1^{+0.5}_{-0.4} \text{(stat.)} \pm 0.3 \text{(syst.)} \pm 0.2 \text{(lumi)} \text{ pb} \quad [\text{SM: } 7.2^{+0.3}_{-0.2}] \]

\[ \sigma_{ZZ}^{tot}(7 \text{ TeV}) = 6.7 \pm 0.7 \text{(stat.)}^{+0.4}_{-0.3} \text{(syst.)} \pm 0.3 \text{(lumi)} \text{ pb} \quad [\text{SM: } 5.89^{+0.22}_{-0.18}] \]

Fiducial Cross Sections:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured ( \sigma_{fid} ) [fb]</th>
<th>Theoretical ( \sigma_{fid} ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ZZ \rightarrow e^+e^-e^+e^- )</td>
<td>( 4.6^{+0.8}<em>{-0.7} \text{(stat.)}^{+0.4}</em>{-0.4} \text{(syst.)}^{+0.1}_{-0.1} \text{(lumi.)} )</td>
<td>( 5.3^{+0.2}_{-0.2} )</td>
</tr>
<tr>
<td>( ZZ \rightarrow \mu^+\mu^-\mu^+\mu^- )</td>
<td>( 5.0^{+0.6}<em>{-0.5} \text{(stat.)}^{+0.2}</em>{-0.2} \text{(syst.)}^{+0.2}_{-0.2} \text{(lumi.)} )</td>
<td>( 5.3^{+0.2}_{-0.2} )</td>
</tr>
<tr>
<td>( ZZ \rightarrow e^+e^-\mu^+\mu^- )</td>
<td>( 11.1^{+1.0}<em>{-0.9} \text{(stat.)}^{+0.5}</em>{-0.5} \text{(syst.)}^{+0.3}_{-0.3} \text{(lumi.)} )</td>
<td>( 10.5^{+0.4}_{-0.4} )</td>
</tr>
<tr>
<td>( ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^- )</td>
<td>( 20.7^{+1.3}_{-1.2} \text{(stat.)} \pm 0.8 \text{(syst.)} \pm 0.6 \text{(lumi.)} )</td>
<td>( 21.1^{+0.9}_{-0.7} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured ( \sigma_{fid} ) [fb]</th>
<th>7 TeV</th>
<th>Theoretical ( \sigma_{fid} ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-}^{\text{fid}} )</td>
<td>( 25.4^{+3.3}<em>{-3.0} \text{(stat.)}^{+1.2}</em>{-1.0} \text{(syst.)} \pm 1.0 \text{(lumi.)} )</td>
<td>( 20.9 \pm 0.1 \text{ (stat.)}^{+1.1}_{-0.9} \text{ (theory)} )</td>
</tr>
<tr>
<td>( \sigma_{ZZ^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-}^{\text{fid}} )</td>
<td>( 29.8^{+3.5}<em>{-3.8} \text{(stat.)}^{+1.7}</em>{-1.5} \text{(syst.)} \pm 1.2 \text{(lumi.)} )</td>
<td>( 25.6 \pm 0.1 \text{ (stat.)}^{+1.3}_{-1.1} \text{ (theory)} )</td>
</tr>
<tr>
<td>( \sigma_{ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}}^{\text{fid}} )</td>
<td>( 12.7^{+3.1}<em>{-2.9} \text{(stat.)}^{+1.7}</em>{-1.7} \text{(syst.)} \pm 0.5 \text{(lumi.)} )</td>
<td>( 12.5 \pm 0.1 \text{ (stat.)}^{+1.0}_{-1.1} \text{ (theory)} )</td>
</tr>
</tbody>
</table>
Cross Section Measurements and Comparison with Theory

ATLAS Preliminary

LHC Data 2012 (\sqrt{s}=8 TeV)
- ATLAS ZZ → llll (66<m(ll)<116 GeV) L=20 fb⁻¹
- CMS ZZ → llll (60<m(ll)<120 GeV) L=5.3 fb⁻¹

LHC Data 2011 (\sqrt{s}=7 TeV)
- ATLAS ZZ → ll(ll/\nu\nu) (66<m(ll)<116 GeV) L=4.6 fb⁻¹
- CMS ZZ → llll (60<m(ll)<120 GeV) L=5.0 fb⁻¹

Tevatron (\sqrt{s}=1.96 TeV)
- D0 ZZ → ll(ll/\nu\nu) (60<m(ll)<120 GeV) L=8.6 fb⁻¹
- CDF ZZ → ll(ll/\nu\nu) (on-shell) L=6.0 fb⁻¹
Differential Cross Sections

- Differential cross sections provide detailed comparison with theory, and comparison of kinematic distributions to new theories
- Variables more sensitive to new phenomena: $p_T^Z$, $m_{ZZ}$, $\Delta \Phi(l^+, l^-)$
- Distributions are unfolded to hadron level, accounting for effects of detector resolution, efficiency and acceptance
  - Use response matrix: MC truth (x) & MC reconstruction (y)
Differential Cross Sections

- Differential cross sections provide detailed comparison with theory, and comparison of kinematic distributions to new theories.
- Variables more sensitive to new phenomena: $p_T^Z$, $m^{ZZ}$, $\Delta\Phi(l^+, l^-)$.
- Distributions are unfolded to hadron level, accounting for effects of detector resolution, efficiency and acceptance.
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Differential Cross Sections

- Differential cross sections provide detailed comparison with theory, and comparison of kinematic distributions to new theories.

- Variables more sensitive to new phenomena: $p_{T}^{Z}$, $m_{ZZ}$, $\Delta \Phi(l^{+}, l^{-})$.

- Distributions are unfolded to hadron level, accounting for effects of detector resolution, efficiency and acceptance.
  - Use response matrix: MC truth (x) & MC reconstruction (y).

![Graphs showing differential cross sections](https://via.placeholder.com/150)
Anomalous TGC Limit

- Effective Lagrangian for neutral Triple Gauge Coupling (ZZZ, ZγZ)

\[ L = -\frac{e}{M_Z^2} \left[ f_4^V (\partial_\mu V^{\mu\beta}) Z_a (\partial^a Z_\beta) + f_5^V (\partial^\sigma V_\sigma) \tilde{Z}^{\mu\beta} Z_\beta \right] \]

- Contribution parametrized by (V=Z,γ):
  - Two CP-violating parameters: \( f_Z^4, f_\gamma^4 \)
  - Two CP-conserving parameters: \( f_Z^5, f_\gamma^5 \)
  - Form-factor parametrization with cut-off scale \( \Lambda \) (scale for new physics)

- Anomalous Couplings enhance cross section at high boson transverse momentum (p_\text{T}) or mass scale (M_{ZZ})

- Limit on nATGC determined by number of events binned in p_\text{T}^Z
Anomalous TGC Limit

Anomalous nATGC 95% confidence intervals

<table>
<thead>
<tr>
<th>$\Lambda$</th>
<th>$f_{40}^\gamma$</th>
<th>$f_{40}^Z$</th>
<th>$f_{50}^\gamma$</th>
<th>$f_{50}^Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 TeV</td>
<td>$[-0.022, 0.023]$</td>
<td>$[-0.019, 0.019]$</td>
<td>$[-0.023, 0.023]$</td>
<td>$[-0.020, 0.019]$</td>
</tr>
<tr>
<td>$\infty$</td>
<td>$[-0.015, 0.015]$</td>
<td>$[-0.013, 0.013]$</td>
<td>$[-0.016, 0.015]$</td>
<td>$[-0.013, 0.013]$</td>
</tr>
</tbody>
</table>
Conclusions

- ZZ production cross section measured in ATLAS both at 7 TeV (final results) and at 8 TeV (preliminary results) and compared with SM NLO predictions
- Both fiducial and total cross section measured
- Analyses used full power of the ATLAS detector lepton identification
- Uncertainties on the cross section measurements limited by statistics, even for the full 20 fb$^{-1}$ 8 TeV preliminary results
- For final 7 TeV results included also ZZ* and 2l2$\nu$ channels, unfolded differential cross sections and limit on nATGC
- Analysis ongoing with full 2012 statistics to measure the differential cross sections at 8 TeV and set new nATGC limit