Measurements of the 7 and 8 TeV cross sections for Z→4l in pp collisions with ATLAS detector

Yusheng Wu
University of Michigan
Institute of Physics, Academia Sinica

On behalf of ATLAS Collaboration

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4l production at Z resonance (Z$\rightarrow$4l) at the LHC

- Test of the SM theory in a rare decay channel
- Complementary test of the detector response for H$\rightarrow$4l measurement
- was first observed at the LHC along with the Higgs discovery in H$\rightarrow$ZZ$^*$→4l channel

**Physics Motivation**

- S channel, $\sim$96%*
  * $m_{4l} \in [80, 100]$ GeV, $m_{2l} > 5$ GeV

- T channel, <4%

- gg fusion, $\sim$0.1%

**Measurement**

- Fiducial and total phase space cross section
- Branching fraction of Z→4l

arXiv:1403.5657
Signal Cross Section and Modelling

qq → Z/Z*Z* → 4ℓ modeled by Powheg MC for
- Cross section calculations (NLO QCD)
- Event generations (interfaced to PYTHIA)

gg → ZZ → 4ℓ modeled by GG2ZZ MC for
- Cross section calculations (LO QCD)
- Event generations (interfaced to Herwig/Jimmy)

NLO Calculation by Powheg (CT10 PDF, Scales = m_{4ℓ})
Phase space: 80 < m_{4ℓ} < 100 GeV and m_{ℓ+ℓ-} > 5 GeV

<table>
<thead>
<tr>
<th>Expected quantity</th>
<th>7 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total inclusive cross-section of pp → Z</td>
<td>26.0 ± 0.6 nb</td>
<td>30.3 ± 0.8 nb</td>
</tr>
<tr>
<td>Total cross-section of pp → Z/Z* → 4ℓ(e, μ)</td>
<td>89.97 ± 2.06 fb</td>
<td>104.84 ± 2.50 fb</td>
</tr>
<tr>
<td>Cross-section of pp → Z/Z* → 4e, 4μ</td>
<td>45.78 ± 1.10 fb</td>
<td>53.35 ± 1.24 fb</td>
</tr>
<tr>
<td>Cross-section of pp → Z/Z* → 2e2μ</td>
<td>44.19 ± 1.04 fb</td>
<td>51.49 ± 1.26 fb</td>
</tr>
<tr>
<td>Total t-ch. cross-section of pp → ZZ* → 4ℓ(e, μ)</td>
<td>3.28 ± 0.08 fb</td>
<td>3.80 ± 0.09 fb</td>
</tr>
<tr>
<td>t-ch. cross-section of pp → ZZ* → 4e, 4μ</td>
<td>1.55 ± 0.04 fb</td>
<td>1.79 ± 0.04 fb</td>
</tr>
<tr>
<td>t-ch. cross-section of pp → ZZ* → 2e2μ</td>
<td>1.73 ± 0.04 fb</td>
<td>2.01 ± 0.05 fb</td>
</tr>
<tr>
<td>Branching ratio of Z → 4ℓ(e, μ)</td>
<td>(3.33 ± 0.01) × 10^{-6}</td>
<td></td>
</tr>
</tbody>
</table>

Z→4ℓ is a rare decay
Data

- 4.6 fb−1 at 7 TeV (collected in 2011)
- 20.3 fb−1 at 8 TeV (collected in 2012)
- Trigger efficiencies for 4l event detection: 95 - 99% (2011); 94 – 98% (2012)

Selection

- At least four leptons (need to detect low $p_T$ leptons)
  - $e$: $p_T > 20, 15, 10, 7$ GeV, $|\eta| < 2.5$
  - $\mu$: $p_T > 20, 15, 8, 4$ GeV, $|\eta| < 2.7$
  - Requirements on identification, isolation and impact parameters

- Mass cut
  - Require two same flavor, opposite charge pairs
    - Leading pair (lepton index 1,2): mass closest to PDG Z mass
    - Sub-leading pair (lepton index 3,4): largest mass of remaining
    - Four decay channels: $4e$, $4\mu$, $2e2\mu$, $2\mu2e$ (leading pair at first)
  - $\Delta R(\ell, \ell') > 0.1(0.2)$ for same flavor (opposite flavor) leptons
  - $m_{12}(\ell^+\ell^-) > 20$ GeV, $m_{34}(\ell^+\ell^-) > 5$ GeV
  - $80$ GeV < $m_{4l}$ < $100$ GeV
Backgrounds

- Diboson: estimated from MC samples
  - Include WZ, $\tau$ decays from ZZ
  - Major uncertainties: MC statistics, lepton efficiency measurement, cross sections, luminosities
- Top and Z+jets: estimated from data

<table>
<thead>
<tr>
<th></th>
<th>7 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>0.06 ± 0.01</td>
<td>0.49 ± 0.04</td>
</tr>
<tr>
<td>Top, Z+jets</td>
<td>0.38 ± 0.14</td>
<td>0.49 ± 0.10</td>
</tr>
</tbody>
</table>

Very clean signature, overall backgrounds <1% of observed events
Top ($t\bar{t}$, Wt) and Z+jet backgrounds

- Two genuine leptons and two leptons from jet faking
- Data-driven method
  - Control region (CR): follow nominal selection but require two of the leptons to be jet faking (loosening or inverting lepton selection cuts)
Top (t\bar{t}, Wt) and Z+jet backgrounds (Cont.)

- Data-driven method
  - Fake factor: measure from jets in Z+jet/Top enriched data events
    
    \[ f = \frac{N_j \text{(pass full lepton selection)}}{N_j \text{(fail full lepton selection)}} \]

  - Top enriched definition: e\mu+MET \rightarrow derive default \mu fake-factor
  - Z+jet enriched: ee/\mu\mu \rightarrow derive default e fake-factor

- Results: 
  \[ N_{\text{Top+Zj}} = N_{CR} \times f_1 f_2 \]

- Major systematics: CR definition, Jet compositions, Data statistics

**\mu** fake-factor from Top enriched region

**e** fake-factor from Z+jet enriched region
Fiducial volume (F.V.) defined at particle level

\[ p_T^\ell 1 > 20 \text{ GeV}; \quad p_T^\ell 2 > 15 \text{ GeV}; \]
\[ p_T^\ell 3 > 10 \text{ GeV} \text{ (if electron)}, \quad > 8 \text{ GeV} \text{ (if muon)}; \]
\[ p_T^\ell 4 > 7 \text{ GeV} \text{ (if electron)}, \quad > 4 \text{ GeV} \text{ (if muon)}; \]
\[ |\eta^\mu| < 2.7 \text{ for all muons}; \quad |\eta^e| < 2.5 \text{ for all electrons}; \]
\[ \Delta R(\ell, \ell') > 0.1 \text{ for all same flavor pairings and } > 0.2 \text{ for different flavor pairings}; \]
\[ M_{\ell+\ell^-} > 20 \text{ GeV} \text{ for at least one SFOS lepton pair}; \]
\[ M_{\ell+\ell^-} > 5 \text{ GeV} \text{ for all SFOS lepton pair}; \]
\[ 80 < M_{4\ell} < 100 \text{ GeV}. \]

\[ A_{4\ell} = \frac{N_{4\ell} \text{ (in F.V.)}}{N_{4\ell} \text{ (in P.S.)}} \quad \quad \quad \quad C_{4\ell} = \frac{N_{4\ell} \text{ (pass full selection)} \text{ (in F.V.)}}{N_{4\ell} \text{ (in F.V.)}} \]

<table>
<thead>
<tr>
<th></th>
<th>eeee</th>
<th>eemµ</th>
<th>µee</th>
<th>µµµµ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 TeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_{4\ell}</td>
<td>7.5%</td>
<td>15.8%</td>
<td>8.8%</td>
<td>18.3%</td>
</tr>
<tr>
<td>C_{4\ell}</td>
<td>21.5%</td>
<td>49.0%</td>
<td>36.3%</td>
<td>59.2%</td>
</tr>
<tr>
<td><strong>8 TeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_{4\ell}</td>
<td>7.3%</td>
<td>14.8%</td>
<td>7.9%</td>
<td>17.8%</td>
</tr>
<tr>
<td>C_{4\ell}</td>
<td>36.1%</td>
<td>55.5%</td>
<td>46.2%</td>
<td>71.1%</td>
</tr>
</tbody>
</table>

Uncertainty on A: 1.3~1.7% (PDF, Scale)

Uncertainty on C: 3-9% (e/µ energy scale/resolution)

Statistical uncertainty still larger than Syst.
Observation and Prediction

7+8TeV:
Observed 172 events
Predicted 170 events

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$4\ell$ state</th>
<th>$N_{4\ell}^{obs}$</th>
<th>$N_{4\ell}^{exp}$</th>
<th>$N_{4\ell}^{bkg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$ee + ee$</td>
<td>1</td>
<td>1.8 ± 0.3</td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + \mu\mu$</td>
<td>8</td>
<td>11.3 ± 0.5</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>$ee + \mu\mu$</td>
<td>7</td>
<td>7.9 ± 0.4</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + ee$</td>
<td>5</td>
<td>3.3 ± 0.3</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>combined</td>
<td>21</td>
<td>24.2 ± 1.2</td>
<td>0.44 ± 0.14</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$ee + ee$</td>
<td>16</td>
<td>14.4 ± 1.4</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + \mu\mu$</td>
<td>71</td>
<td>68.8 ± 2.7</td>
<td>0.34 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>$ee + \mu\mu$</td>
<td>48</td>
<td>43.2 ± 2.1</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu + ee$</td>
<td>16</td>
<td>19.3 ± 1.3</td>
<td>0.18 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>combined</td>
<td>151</td>
<td>146 ± 7</td>
<td>1.0 ± 0.11</td>
</tr>
</tbody>
</table>
Cross Section Measurement

- The 4e and 4\(\mu\) channels, and The 2e2\(\mu\) and 2\(\mu\)2e channels are combined with 2x2 covariance error matrices for \(\sigma\) measurement.

- The 4l \(\sigma^{\text{total}} = \sigma(4e+4\mu) + \sigma(2e2\mu)\), uncertainties are determined by 4x4 error matrices.

- SM NLO Prediction for Total \(\sigma\): \(90.0 \pm 2.1\) fb (7TeV), \(104.8 \pm 2.5\) fb (8TeV)
The Z→4l branching fraction

\[ \text{BR}(Z \rightarrow 4\ell) = \text{BR}(Z \rightarrow 2\mu)(1-f_t) \frac{(N_{\text{obs}} - N_{\text{bkg}})^{4\ell}(C \times A)^{2\mu}}{(N_{\text{obs}} - N_{\text{bkg}})^{2\mu}(C \times A)^{4\ell}} \]

Uncertainty on \( \text{BR}(Z \rightarrow 2\mu) \) is small. \( f_t \) = fraction of t-channel in phase-space.

- Measure the pp→Z→μμ cross section from data and use well known Br(Z→μμ) to get inclusive pp→Z cross section
- Luminosity and Theoretical uncertainties cancel due to the ratio

Results

- \( \text{Br}(Z \rightarrow 4\ell) \) defined under phase space \( m_{2\ell} > 5 \text{ GeV}, 80 < m_{4\ell} < 100 \text{ GeV} \)
- 7 TeV and 8 TeV results combined with error weighting

<table>
<thead>
<tr>
<th>Quantity</th>
<th>( \sqrt{s} )</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>7 TeV</td>
<td>((2.67 \pm 0.62 \text{ (stat)} \pm 0.14 \text{ (syst)}) \times 10^{-6})</td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>((3.33 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)}) \times 10^{-6})</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>((3.20 \pm 0.25 \text{ (stat)} \pm 0.12 \text{ (syst)}) \times 10^{-6})</td>
</tr>
<tr>
<td>Expected</td>
<td></td>
<td>((3.33 \pm 0.01) \times 10^{-6})</td>
</tr>
</tbody>
</table>
4l mass fitted with the convolution of a Breit-Wigner and a Gaussian distribution for four 4l channels shown good consistence with MC predictions. Example of 4µ mass fit for data and MC

\begin{align*}
\text{ATLAS Preliminary} & \quad \text{Mean} = 90.63 \pm 0.29 \\
\int \text{Ldt} = 20.6 \text{ fb}^{-1} & \quad \text{RMS} = 3.75 \pm 0.20 \\
\sqrt{s} = 8 \text{ TeV} & \quad m_{4l} = 90.75 \pm 0.29 \\
Z/Z^* \rightarrow \mu^+ \mu^- \mu^+ \mu^- & \quad \sigma_{4l} = 2.58 \pm 0.33
\end{align*}

\begin{align*}
\text{ATLAS Simulation} & \quad \text{Mean} = 90.73 \pm 0.03 \\
\sqrt{s} = 8 \text{ TeV} & \quad \text{RMS} = 3.48 \pm 0.02 \\
Z/Z^* \rightarrow \mu^+ \mu^- \mu^+ \mu^- & \quad m_{4l} = 91.04 \pm 0.03 \\
& \quad \sigma_{4l} = 1.95 \pm 0.03
\end{align*}
The cross-section measurements of 4l production at Z resonance at ATLAS using 7 TeV and 8 TeV pp collision data are presented, the results are consistent with NLO SM prediction.

The rare Z→4l branching fraction is also calculated, which is in good agreement with SM prediction.

Current results are limited in statistical uncertainty, more data will be needed for better precision.
ATLAS (A Toroidal LHC ApparatuS): 44×25m, 7000t
Inner tracking $|\eta|<2.5$, EM calo $|\eta|<3.2$, Hadronic calo $|\eta|<4.9$, Muon system $|\eta|<2.7$
ATLAS collaboration 3k physicists from 38 countries
CalcHEP MC (LO QCD) used to calculate the magnitude of interference between the s-channel and the t-channel 4\ell production processes

- \sim 0.2% in the 4\ell phase space

  80 < m_{4\ell} < 100 \text{ GeV}, \ m_{2\ell}>5 \text{ GeV}

- treat it as systematic uncertainty when determining the \text{Z} \rightarrow 4\ell branching fraction
Good data and MC agreement in lepton kinematic distributions

\textit{ATLAS} \hspace{1cm} \begin{align*}
& |s| = 7 \text{ TeV, } 4.5 \text{ fb}^{-1} \\
& |s| = 8 \text{ TeV, } 20.3 \text{ fb}^{-1} \end{align*}