Measurements of the 7 and 8 TeV cross sections for \( Z \rightarrow 4l \) in pp collisions with ATLAS and CMS

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Introduction

- The Z→4ℓ production was first observed at the LHC by both ATLAS and CMS experiments along with the Higgs boson discovery in the 4ℓ decay channel
- Cross section measurement of the Z→4ℓ production provides
  - A SM test for a rare decay process (measurements of \(\sigma(4\ell)\) and \(\text{BR}(Z\rightarrow4\ell)\))
  - A complementary test of the detector response for H→4ℓ detection

References:

**4\ell Production at Z Resonance**

- **Four lepton final states:** 4e, 4\(\mu\) and 2e2\(\mu\)

- **Resonant 4\ell production** via an s-channel
  -- \(Z \rightarrow \ell^+\ell^-\) include an additional \(\ell^+\ell^-\) from internal conversion of \(Z^*/\gamma^*\)
  -- s-channel is dominant
    ( >96% for 80 < \(m_{4\ell}\) < 100 GeV, \(m_{2\ell} > 5\) GeV)

- **Non-resonant 4\ell production**
  - via t-channel: \(qq \rightarrow Z^*/\gamma^* + Z^*/\gamma^* \rightarrow 4\ell\) including the Z production with ISR internal conversion (< 4% 4\ell event rate at the Z resonance)
  - via \(gg \rightarrow ZZ \rightarrow 4\ell\) (~0.1% 4\ell event rate at the Z resonance)
**4ℓ Production Modeling**

- **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)

- **MCFM MC** used to cross check cross sections

- **CalcHEP MC (LO QCD)** used to calculate the magnitude of interference between the s-channel and the t-channel 4ℓ production processes
  - ~0.2% in the 4ℓ phase space
    - 80 < m_{4ℓ} < 100 GeV, m_{2ℓ} > 5 GeV
  - treat it as systematic uncertainty when determine the Z → 4ℓ branching fraction
Z→4l Is A Rare Decay

- No measurement before the LHC
- NLO Calculation by Powheg MC (PDF: CT10, Scales: m_{4\ell}) in a phase space: \(80 < m_{4\ell} < 100\) GeV and \(m_{\ell^+\ell^-} > 5\) 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 \rightarrow Z)</td>
<td>26.0 ± 0.6 nb</td>
<td>30.3 ± 0.8 nb</td>
</tr>
<tr>
<td>Total cross-section of (pp \rightarrow Z/ZZ^* \rightarrow 4\ell(e, \mu))</td>
<td>89.97 ± 2.06 fb</td>
<td>104.84 ± 2.50 fb</td>
</tr>
<tr>
<td>Cross-section of (pp \rightarrow Z/ZZ^* \rightarrow 4e, 4\mu)</td>
<td>45.78 ± 1.10 fb</td>
<td>53.35 ± 1.24 fb</td>
</tr>
<tr>
<td>Cross-section of (pp \rightarrow Z/ZZ^* \rightarrow 2e2\mu)</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 \rightarrow ZZ^* \rightarrow 4\ell(e, \mu))</td>
<td>3.28 ± 0.08 fb</td>
<td>3.80 ± 0.09 fb</td>
</tr>
<tr>
<td>t-ch. cross-section of (pp \rightarrow ZZ^* \rightarrow 4e, 4\mu)</td>
<td>1.55 ± 0.04 fb</td>
<td>1.79 ± 0.04 fb</td>
</tr>
<tr>
<td>t-ch. cross-section of (pp \rightarrow ZZ^* \rightarrow 2e2\mu)</td>
<td>1.73 ± 0.04 fb</td>
<td>2.01 ± 0.05 fb</td>
</tr>
<tr>
<td>Branching ratio of (Z \rightarrow 4\ell(e, \mu))</td>
<td>((3.33 ± 0.01) \times 10^{-6})</td>
<td></td>
</tr>
</tbody>
</table>

- For a larger phase space \(80 < m_{4\ell} < 100\) GeV, \(m_{\ell^+\ell^-} > 4\) GeV, the inclusive \(4\ell\) cross section is 35% higher
Measurement Approaches

• **ATLAS (with data collected at 7 and 8 TeV)**
  - Measure *inclusive* $4\ell$ production cross-section at the Z resonance, i.e. the non-resonance $4\ell$ events are treated as *signal* → cross section measurement will be less depending on theory interpretation; measured both *fiducial* and *final phase space* cross sections.
  - In determination of $Z\rightarrow4\ell$ decay branching fraction, the non-resonance $4\ell$ contribution is subtracted and the resonance $4\ell$ event yield is normalized by the $Z\rightarrow\mu\mu$ with the same dataset.

• **CMS (with data collected at 7 TeV)**
  - Measure the resonance $Z\rightarrow4\ell$ production cross section, and treat the t-channel $4\ell$ events as background.
  - Using the $Z\rightarrow\mu\mu$ events to normalize the $Z\rightarrow4\ell$ events to determine the BR($Z\rightarrow4\ell$).

• **Phase space for measurements**
  - **ATLAS:** $80 < m_{4\ell} < 100$ GeV and $m_{\ell^+\ell^-} > 5$ GeV; also measured BR in a larger phase space: $m_{\ell^+\ell^-} > 4$ GeV.
  - **CMS:** $80 < m_{4\ell} < 100$ GeV, $m_{\ell\ell} > 4$ GeV (for any pairs of leptons).
Data Sets for $Z \rightarrow 4\ell$ Analysis

- **ATLAS**
  - 4.6 fb$^{-1}$ at 7 TeV (collected in 2011);
  - 20.3 fb$^{-1}$ at 8 TeV (collected in 2012)
  - In detection fiducial volume, trigger efficiencies for $4\ell$ event detection: 95 - 99% (2011); 94 – 98% (2012)

- **CMS**
  - 5.0 fb$^{-1}$ at 7 TeV (collected in 2010 and 2011)
  - In detection fiducial volume, trigger efficiencies: 96 – 99%
Experimental Challenge to Detect $Z \rightarrow 4\ell$

- The $Z \rightarrow 4\ell$ process is dominant by low mass $m_{34}$ and low pT leptons (the pT-ordered 4th leptons)
- Need to detect low pT leptons

**ATLAS $Z \rightarrow 4\ell$ selection:**

- $e$: $p_T > 20, 15, 10, 7$ GeV, $|\eta| < 2.5$
- $\mu$: $p_T > 20, 15, 8, 4$ GeV, $|\eta| < 2.7$
- $m_{12} (\ell^+\ell^-) > 20$ GeV, $m_{34} (\ell^+\ell^-) > 5$ GeV
- $80 \text{ GeV} < m_{4\ell} < 100$ GeV

**CMS $Z \rightarrow 4\ell$ selection:**

- $e$: $p_T > 20, 10, 7, 7$ GeV, $|\eta| < 2.5$
- $\mu$: $p_T > 20, 10, 5, 5$ GeV, $|\eta| < 2.4$
- $m_\mu > 4$ GeV
- $80 \text{ GeV} < m_{4\ell} < 100$ GeV
Event Display of $Z\rightarrow 4\mu$

CMS
Run: 180076
Event: 456795917

$pT_1: 43.76$ GeV
$pT_2: 24.20$ GeV
$pT_3: 10.51$ GeV
$pT_4: 7.39$ GeV

$M_{Z1}: 62.58$ GeV
$M_{Z2}: 17.27$ GeV
$M_{4L}: (91.30 \pm 0.61)$ GeV

Min(mass2l): 12.22 GeV
Max(mass2l): 62.58 GeV

Figure 5: Event display of a typical event from the peak at the Z boson mass.
Muon Momentum Scale and Resolution

ATLAS

Muon energy scale and resolution corrections and systematic uncertainties determined from large Z, J/ψ and Y samples

- Resolution correction (0.2-1.3%), scale correction (< 0.1%)
- Independent measurements from Muon Spectrometer and inner tracker
- Probe global and local scale biases, overall uncertainty on 4µ scale 0.2%
- Calibration using Z → 4µ mass peak (with m_{2l} > 1 GeV)

Comparison to PDG value
EM Calorimeter Calibration

- In-situ energy calibration results and their stability checked with different methods (E/P with $W \rightarrow e\nu$, $Z \rightarrow ee$, and $J/\psi \rightarrow ee$)

- Uncertainty on the diphoton mass scale 0.6%, largely contributions
  - Material effects (separately for volumes for $|\eta| < 1.8$, and $|\eta| > 1.8$)
  - Uncertainty on the in-situ calibration method

Stability of EM calorimeter response vs time/pile-up better than 0.1%
Acceptance $A_{4\ell}$, Correction Factor $C_{4\ell}$, $\sigma_{\text{fid}}$ and $\sigma_{\text{total}}$

Fiducial volume definition

$\frac{1}{p_T^\ell_1} > 20 \text{ GeV}; \frac{1}{p_T^\ell_2} > 15 \text{ GeV};$
$\frac{1}{p_T^\ell_3} > 10 \text{ GeV} \text{ (if electron)}, > 8 \text{ GeV} \text{ (if muon)};
\frac{1}{p_T^\ell_4} > 7 \text{ GeV} \text{ (if electron)}, > 4 \text{ GeV} \text{ (if muon)};
\frac{| \eta^\mu |}{\eta^\ell} < 2.7 \text{ for all muons; } | \eta^e | < 2.5 \text{ for all electrons};
\Delta R(\ell, \ell') > 0.1 \text{ for all same flavor pairings and } > 0.2 \text{ for different flavor pairings};
M_{\ell^+\ell^-} > 20 \text{ GeV for at least one SFOS lepton pair};
M_{\ell^+\ell^-} > 5 \text{ GeV for all SFOS lepton pair};
80 < M_{4\ell} < 100 \text{ GeV}.$

Acceptance factors:

$C_{4\ell} = \frac{N_{4\ell}}{N_{4\ell}} \text{ (pass full selection)/ } \frac{N_{4\ell}}{N_{4\ell}} \text{ (in F. V.)}$

$A_{4\ell} = \frac{N_{4\ell}}{N_{4\ell}} \text{ (in F. V.)/ } \frac{N_{4\ell}}{N_{4\ell}} \text{ (in P. S.)}$

$\sigma_{\text{fiducial}}$ and $\sigma_{\text{total}}$:

$\sigma_{\text{Z} \rightarrow 4\ell}^{\text{fiducial}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L}C_{\text{Z} \rightarrow 4\ell}}$

$\sigma_{\text{Z} \rightarrow 4\ell}^{\text{total}} = \frac{\sigma_{\text{Z} \rightarrow 4\ell}^{\text{fiducial}}}{A_{\text{Z} \rightarrow 4\ell}}$
The uncertainties on $A_{4l}$ are theoretical due to scales and PDF (1.3 - 1.7%). The uncertainties on $C_{4l}$ are mainly experimental: lepton reconstruction and identification efficiencies and energy/momentum scales and resolution; $\Delta C_{4l}/C_{4l}$: 2.7%, 3.7%, 6.2% and 9.4% for 4m, eeμμ, μμee and 4e channel, respectively (at 8 TeV).

Larger $C_{4l}$ values at 8 TeV due to lepton recon. And ID improvements.

Currently statistical uncertainties are larger than the systematic uncertainties.
Data Driven Top and Z+jet Background Estimation

ATLAS

- Select the $\ell\ell+jj_{\ell}$ background control samples, where $jj_{\ell}$ are two lepton-like jets (selected with invert lepton selection cuts)

- MC background control samples indicate the jet compositions

- Each event in the control samples is scaled by a fake-factor product $f_1xf_2$ to estimate the background in the signal region

- $f$ is determined using jet enriched ttbar and Z+jet samples
Determination of Fake-Factor $f$

$$f = \frac{N_j \text{ (pass full lepton selection)}}{N_j \text{ (fail full lepton selection)}}$$

Select $j_\mu$ in the control sample with $e_\mu + E_T^{\text{miss}}$

Select $j_e$ in the control sample with $Z \rightarrow \ell\ell$
Summary of Estimated Background

ATLAS

Dibosons (including \( \tau \) final states and gg production) estimated with MC, \( t\bar{t} \) and \( Z + X \) estimated with data and fake factor as before.

<table>
<thead>
<tr>
<th>Year</th>
<th>Channel</th>
<th>diboson from MC</th>
<th>( Z+\text{jet and } t\bar{t} ) from data-driven</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>4e</td>
<td>0.010 ± 0.002</td>
<td>0.11 ± 0.05</td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>2e2( \mu )</td>
<td>0.024 ± 0.002</td>
<td>0.16 ± 0.09</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>2( \mu )2e</td>
<td>0.015 ± 0.002</td>
<td>0.06 ± 0.03</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>4( \mu )</td>
<td>0.038 ± 0.003</td>
<td>0.05 ± 0.04</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>2012</td>
<td>4e</td>
<td>0.064 ± 0.009</td>
<td>0.10 ± 0.01</td>
<td>0.16 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>2e2( \mu )</td>
<td>0.156 ± 0.019</td>
<td>0.20 ± 0.05</td>
<td>0.36 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>2( \mu )2e</td>
<td>0.132 ± 0.017</td>
<td>0.08 ± 0.02</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>4( \mu )</td>
<td>0.301 ± 0.026</td>
<td>0.11 ± 0.05</td>
<td>0.41 ± 0.05</td>
</tr>
</tbody>
</table>

Remark:
- Overall background contribution to selected 4l sample is < 1%
- Likelihood e-ID significantly reduce the fake electron rate in 2012 data analysis
## Selected Candidates

### Observation vs Predictions

#### ATLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Data</th>
<th>Total expected</th>
<th>MC signal ($Z/ZZ \rightarrow 4\ell$)</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$eeee$</td>
<td>1</td>
<td>$1.8 \pm 0.3$</td>
<td>$1.7 \pm 0.3$</td>
<td>$0.12 \pm 0.04$</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>7</td>
<td>$8.0 \pm 0.4$</td>
<td>$7.7 \pm 0.4$</td>
<td>$0.18 \pm 0.09$</td>
</tr>
<tr>
<td>$\mu\mu ee$</td>
<td>5</td>
<td>$3.3 \pm 0.3$</td>
<td>$3.2 \pm 0.3$</td>
<td>$0.08 \pm 0.04$</td>
</tr>
<tr>
<td>$\mu\mu\mu\mu$</td>
<td>8</td>
<td>$11.3 \pm 0.5$</td>
<td>$11.2 \pm 0.3$</td>
<td>$0.09 \pm 0.04$</td>
</tr>
<tr>
<td>Combined</td>
<td>21</td>
<td>$24.4 \pm 1.2$</td>
<td>$23.8 \pm 1.2$</td>
<td>$0.47 \pm 0.11$</td>
</tr>
<tr>
<td>8 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$eeee$</td>
<td>16</td>
<td>$14.4 \pm 1.2$</td>
<td>$14.3 \pm 1.2$</td>
<td>$0.16 \pm 0.03$</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>48</td>
<td>$43.2 \pm 2.3$</td>
<td>$42.9 \pm 2.2$</td>
<td>$0.36 \pm 0.05$</td>
</tr>
<tr>
<td>$\mu\mu ee$</td>
<td>16</td>
<td>$19.3 \pm 1.2$</td>
<td>$19.1 \pm 1.2$</td>
<td>$0.21 \pm 0.04$</td>
</tr>
<tr>
<td>$\mu\mu\mu\mu$</td>
<td>71</td>
<td>$68.8 \pm 3.0$</td>
<td>$68.4 \pm 2.9$</td>
<td>$0.41 \pm 0.05$</td>
</tr>
<tr>
<td>Combined</td>
<td>151</td>
<td>$145.7 \pm 7.7$</td>
<td>$145 \pm 7$</td>
<td>$1.14 \pm 0.13$</td>
</tr>
</tbody>
</table>

#### CMS (7 TeV)

<table>
<thead>
<tr>
<th>Final state channels</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irreducible background ($pp \rightarrow Z\gamma^* \rightarrow 4\ell$)</td>
<td>0.07</td>
<td>0.25</td>
<td>0.14</td>
<td>$0.46 \pm 0.05$</td>
</tr>
<tr>
<td>Other (reducible) backgrounds</td>
<td>0.01</td>
<td>0.01</td>
<td>0.05</td>
<td>$0.07 \pm 0.1$</td>
</tr>
<tr>
<td>Expected signal ($pp \rightarrow Z \rightarrow 4\ell$)</td>
<td>3.8</td>
<td>13.6</td>
<td>12.0</td>
<td>$29.4 \pm 2.6$</td>
</tr>
<tr>
<td>Total expected (simulation)</td>
<td>3.9</td>
<td>13.9</td>
<td>12.2</td>
<td>$30.0 \pm 2.6$</td>
</tr>
<tr>
<td>Observed events</td>
<td>2</td>
<td>14</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td>Yield from fit to the observed mass distribution</td>
<td>-</td>
<td>$13.6 \pm 3.8$</td>
<td>$11.5 \pm 3.1$</td>
<td>$27.3 \pm 5.4$</td>
</tr>
</tbody>
</table>
Figure 2: Four-lepton invariant mass distribution for events passing all selection requirements except that on $m_{4\ell}$. The data are shown by points. The filled histograms represent standard model expectations for pp $\rightarrow Z/Z\gamma^* \rightarrow 4\ell$ and for reducible backgrounds. The three final states, 4e, 4\mu, and 2e2\mu, are combined.
FIG. 2. Invariant mass distributions of (a) the leading lepton pair, $m_{12}$, (b) the subleading lepton pair, $m_{34}$, and (c) the four-lepton system, $m_{4\ell}$. The MC simulation expectation for a combination of all channels is compared to $\sqrt{s} = 7$ and 8 TeV data. All selections are applied except in (c) there is no $m_{4\ell}$ requirement. The background contributes $< 1\%$ of the total expected signal (invisible in the plots).
pT of Leptons

Good data and MC agreement in lepton kinematic distributions
# Measured Fiducial Cross Sections

$$\sigma_{Z\rightarrow 4\ell}^{fiducial} = \frac{N_{obs} - N_{bkg}}{L C_{Z\rightarrow 4\ell}}$$

## ATLAS

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Final state</th>
<th>$C_{4\ell}$</th>
<th>Measured $\sigma^{Fid}$ fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$eeee$</td>
<td>21.5%</td>
<td>$0.910^{+1.39}_{-0.72}$ (stat) ± 0.14 (syst) ± 0.02 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu\mu\mu$</td>
<td>59.2%</td>
<td>$2.970^{+1.18}_{-0.94}$ (stat) ± 0.07 (syst) ± 0.05 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$ee\mu\mu$</td>
<td>49.0%</td>
<td>$3.091^{+1.35}_{-1.05}$ (stat) ± 0.16 (syst) ± 0.05 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu ee$</td>
<td>36.3%</td>
<td>$3.015^{+1.57}_{-1.17}$ (stat) ± 0.30 (syst) ± 0.06 (lumi) fb</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$eeee$</td>
<td>36.06%</td>
<td>$2.16^{+0.59}_{-0.50}$ (stat) ± 0.16 (syst) ± 0.06 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu\mu\mu$</td>
<td>71.13%</td>
<td>$4.89^{+0.66}_{-0.56}$ (stat) ± 0.13 (syst) ± 0.14 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$ee\mu\mu$</td>
<td>55.54%</td>
<td>$4.23^{+0.65}_{-0.59}$ (stat) ± 0.15 (syst) ± 0.12 (lumi) fb</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu ee$</td>
<td>46.24%</td>
<td>$1.68^{+0.46}_{-0.39}$ (stat) ± 0.07 (syst) ± 0.04 (lumi) fb</td>
</tr>
</tbody>
</table>
$\sigma_{4l}$ measurement in final phase-space

ATLAS measurement in final phase space
$80 < m_{4l} < 100$ GeV and $m_{e+e-} > 5$ GeV

- 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.

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>4l state</th>
<th>$N_{4l}^{obs}$</th>
<th>$N_{4l}^{exp}$</th>
<th>$N_{4l}^{bkg}$</th>
<th>$C_{4l}$</th>
<th>$\sigma_{Z4l}^{fid}$ [fb]</th>
<th>$A_{4l}$</th>
<th>$\sigma_{Z4l}$ [fb]</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>
<td>21.5%</td>
<td>0.9^{+1.4}_{-0.7} ± 0.14 ± 0.02</td>
<td>7.5%</td>
<td>32 ± 11 ± 1.0 ± 0.6</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>
<td>59.2%</td>
<td>3.0^{+1.2}_{-0.9} ± 0.07 ± 0.05</td>
<td>18.3%</td>
<td>44 ± 14 ± 3.3 ± 0.9</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>
<td>49.0%</td>
<td>3.1^{+1.4}_{-1.1} ± 0.16 ± 0.05</td>
<td>15.8%</td>
<td>76 ± 18 ± 4 ± 1.4</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>
<td>36.3%</td>
<td>3.0^{+1.6}_{-1.2} ± 0.30 ± 0.06</td>
<td>8.8%</td>
<td>56 ± 6 ± 1.8 ± 1.6</td>
</tr>
<tr>
<td>combined</td>
<td>21</td>
<td>24.2 ± 1.2</td>
<td>0.44 ± 0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 8 TeV | ee + ee | 16 | 14.4 ± 1.4 | 0.14 ± 0.03 | 36.1% | 2.2^{+0.6}_{-0.5} ± 0.20 ± 0.06 | 7.3% | 56 ± 6 ± 1.8 ± 1.6 |
| | $\mu\mu + \mu\mu$ | 71 | 68.8 ± 2.7 | 0.34 ± 0.05 | 71.1% | 4.9^{+0.7}_{-0.6} ± 0.13 ± 0.14 | 17.8% | 52 ± 7 ± 2.4 ± 1.5 |
| | ee + $\mu\mu$ | 48 | 43.2 ± 2.1 | 0.32 ± 0.05 | 55.5% | 4.2^{+0.7}_{-0.6} ± 0.16 ± 0.12 | 14.8% | 107 ± 9 ± 4 ± 3.0 |
| | $\mu\mu + ee$ | 16 | 19.3 ± 1.3 | 0.18 ± 0.04 | 46.2% | 1.7^{+0.5}_{-0.4} ± 0.10 ± 0.04 | 7.9% | |
### ATLAS

<table>
<thead>
<tr>
<th></th>
<th>Phase-space cross section (m_{2l} &gt; 5 GeV, 80 &lt; m_{4l} &lt; 100 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 TeV measured</strong></td>
<td>76 ± 18 (stat.) ± 4 (syst.) ± 1.4 (lumi.) fb</td>
</tr>
<tr>
<td><strong>7 TeV NLO SM prediction</strong></td>
<td>90.0 ± 2.1 fb</td>
</tr>
<tr>
<td><strong>8 TeV measured</strong></td>
<td>107 ± 9 (stat.) ± 4 (syst.) ± 3.0 (lumi.) fb</td>
</tr>
<tr>
<td><strong>8 TeV NLO SM prediction</strong></td>
<td>104.8 ± 2.5 fb</td>
</tr>
</tbody>
</table>

### CMS

<table>
<thead>
<tr>
<th></th>
<th>Phase-space cross section (m_{2l} &gt; 4 GeV, 80 &lt; m_{4l} &lt; 100 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 TeV measured</strong></td>
<td>112^{+23}<em>{-20} (stat.) ^{+7}</em>{-5} (syst.) ^{+3}_{-2} (lumi.) fb</td>
</tr>
<tr>
<td><strong>7 TeV NLO SM prediction</strong></td>
<td>120 ± 2.1 fb</td>
</tr>
</tbody>
</table>
Determination of BR(\(Z \rightarrow 4\ell\))

ATLAS

- Measure the \(Z \rightarrow 2\mu\) cross section and take the known \(\text{Br}(Z \rightarrow 2\mu)\) to get inclusive cross section of \(Z\) from pp collisions
- Cancels luminosity uncertainty and theoretical uncertainty of \(\sigma(pp \rightarrow Z)\)
- Derive the BR (\(\text{BR}(Z \rightarrow 4\ell)\)) as below

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

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

- \(f_t = (3.35 \pm 0.02)\%\) for \(4e, 4\mu\); \(f_t = (3.90 \pm 0.02)\%\) for \(2e2\mu\)

- Cancel luminosity uncertainty: 2.8% \((8\text{ TeV})\)
- Cancel NLO \(\sigma(Z)\) calculation uncertainties (Scales, PDF, NNLO correction): 4%
Branching Fraction of $Z \to 4\ell$

Branching fraction results uses an error weighted combination of 7 and 8 TeV results. For phase space $m_{2\ell} > 5$ GeV, $80 < m_{4\ell} < 100$ GeV.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\sqrt{s}$</th>
<th>Value</th>
<th>ATLAS</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>
<td>$(3.33 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)}) \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>8 TeV</td>
<td>$(3.20 \pm 0.25 \text{ (stat)} \pm 0.12 \text{ (syst)}) \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>$(3.33 \pm 0.01) \times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

For phase space $m_{2\ell} > 4$ GeV, $80 < m_{4\ell} < 100$ GeV:

<table>
<thead>
<tr>
<th></th>
<th>BR (measured)</th>
<th>BR (predicted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$(4.31 \pm 0.34 \pm 0.17) \times 10^{-6}$</td>
<td>$(4.50 \pm 0.01) \times 10^{-6}$</td>
</tr>
<tr>
<td>CMS</td>
<td>$(4.2^{+0.9}_{-0.8} \pm 0.2) \times 10^{-6}$</td>
<td>$4.45 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
From the fit results, as shown in Fig. above, one can see that the offset of the peak is $0.4 \pm 0.4 \text{ GeV}$ (to the right) (the “mean” value of the Crystal Ball function represents an offset with respect to the fixed Breit–Wigner function peak position), or, in relative units, $0.4 \pm 0.4\%$. These numbers can be used to constrain the possible systematic uncertainty of the four-lepton mass scale. With the current data there is no evidence for a statistically significant bias.
4\ell mass fitted with the convolution of a Breit-Wigner and a Gaussian distribution for four 4\ell channels shown good consistence with MC predictions. Example of 4\mu mass fit for data and MC

Invariant mass distributions of 4\mu, fitted with the convolution of a Breit-Wigner and a Gaussian distribution, for the reconstructed events within the Z-mass window of 80 to 100 GeV using (a) 4\mu data, (b) simulated Z\rightarrow 4\mu. All for 8 TeV datasets using relaxed dilepton mass requirement in event selection, m_{2\ell} > 1 GeV. The parameter m_{4\ell} is the fit mean and \sigma_{4\ell} is the standard deviation of the Gaussian component of the fit.
Summary

• The 4\ell production at the Z resonance has been observed at the LHC by both ATLAS and CMS experiments.

• The 4\ell production cross sections are measured by ATLAS (at 7 and 8 TeV) and by CMS (at 7 TeV). Results are consistent with the SM predictions calculated to NLO (QCD) (Powheg/MCFM).

• The rare decay branching fraction of Z→4\ell is determined from the cross section measurements by normalizing the 4\ell events to the Z→\mu\mu events. Results are consistent within uncertainties from both experiments.

<table>
<thead>
<tr>
<th>Phase Space</th>
<th>BR (measured)</th>
<th>BR (predicted)</th>
</tr>
</thead>
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<tr>
<td><strong>ATLAS</strong></td>
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<td></td>
</tr>
<tr>
<td>80 &lt; m_{4\ell} &lt; 100 GeV and m_{l^+l^-} &gt; 5 GeV</td>
<td>(3.20 ± 0.25 ± 0.13) x 10^{-6}</td>
<td>(3.33 ± 0.01) x 10^{-6}</td>
</tr>
<tr>
<td>80 &lt; m_{4\ell} &lt; 100 GeV and m_{l^+l^-} &gt; 4 GeV</td>
<td>(4.31 ± 0.34 ± 0.17) x 10^{-6}</td>
<td>(4.50 ± 0.01) x 10^{-6}</td>
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<td>4.45 x 10^{-6}</td>
</tr>
</tbody>
</table>

• The 4\ell mass scales and resolutions between data and MC simulations are consistent for both ATLAS and CMS, which provide a good cross-check on the Higgs →4\ell mass measurement.
Backup slides
# ATLAS 4l Event Selection

**Red indicates differences from $H \rightarrow ZZ^* \rightarrow 4\ell$**

| Electrons | GSF electrons selected with Loose++ from the H4l2011 menu (2011) or Loose from the Likelihood menu (2012) with $E_T > 7$ GeV and $|\eta| < 2.47$ |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Muons     | Combined, segment-tagged, calo-tagged ($p_T > 15$ GeV), and stand-alone Staco muons with $p_T > 4$ GeV and $|\eta| < 2.7$ |

## Event Selection

**Quadruplet selection**
- Two pairs of same-flavour opposite-charge leptons.
- The three leading leptons in the quadruplet have $p_T > 20$, 15, and 10 GeV.
- If the third lepton is a muon it may have $p_T > 8$ GeV
- Pick the pair that has $M_{Z1}$ nearest the $Z$-mass, and then a second pair with $M_{Z2}$ greatest.

**Kinematic selection**
- Leading di-lepton pair must have inv. mass $M_{Z1} > 20$ GeV
- Sub-leading di-lepton pair must have inv. mass $M_{Z2} > 5$ GeV
- No same-flavor opposite-charge di-lepton giving $M_{\ell^+\ell^-} < 5$ GeV ($J/\psi$ veto)
- $\Delta R(\ell, \ell') > 0.1$ (0.2) for all same-flavor (opposite-flavor) leptons in the quadruplet.

**Isolation**
- Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T / p_T < 0.15$
- Lepton calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / E_T < 0.30$
- except $< 0.15$ for stand-alone muons and in 2012 $< 0.20$ for electrons,

**Impact parameter significance**
- Apply impact parameter significance cut to all leptons of the quadruplet.
  - For electrons: $d_0 / \sigma_{d0} < 6.5$
  - For muons: $d_0 / \sigma_{d0} < 3.5$

**Four-body mass**
- $80 < m_{4\ell} < 100$ GeV