ATLAS Measurements of Electroweak Boson Production Cross Sections

Christian Göringer for the ATLAS collaboration

Cross section measurements:
• Inclusive W/Z
• W/Z+jets
• Diboson
Introduction

Cross section measurements:

• **Inclusive W/Z**
  – 2010 Dataset 33-36 pb\(^{-1}\)
  – Sensitive to Parton Density Functions (PDFs), W lepton universality

• **W/Z+jets**
  – 2010 Dataset 33-36 pb\(^{-1}\)
  – Test of QCD calculations and MC generators

• **Diboson**
  – 2011 Dataset (till June) 1 fb\(^{-1}\)
  – Sensitive to Triple Gauge Couplings (TGCs)

• **Measurements done with high p\(_T\) electrons and muons**
  – Precise understanding of lepton reconstruction, identification, calibration and resolution in W/Z events required
The ATLAS detector

- Tracking system ($|\eta| < 2.5$)
- Calorimeters (central $|\eta|< 2.5$, forward $|\eta| < 4.9$
- Muon systems ($|\eta| < 2.7$)
Inclusive W and Z

Selection
• High $p_T$ lepton(s) $l=e, \mu$
  – Electrons: $E_T > 20$GeV, Muons: $p_T > 20$GeV, isolated
• Z candidate:
  – Mass in range [66,116] GeV, opposite charge
• W candidate:
  – High missing $E_T$ and $M_T$
• Very clean signal

Detailed background estimation
• Multi-jet (“QCD”) by data driven methods
  – Template fit (cut inversion)
  – Matrix method
• Electroweak from MC
Inclusive W and Z

Fiducial cross section
\[ \sigma_{Fid} = \frac{N_{Obs} - N_{Bkg}}{C \cdot L_{int}} \]

Total cross section
\[ \sigma_{Tot} = \frac{N_{Obs} - N_{Bkg}}{A \cdot C \cdot L_{int}} \]

Uncertainties:
- Luminosity
- Acceptance
- Experimental ~1%
  - W: MET scale and resolution uncertainty
  - W,Z: electron/muon reconstruction and ID efficiency

Individual channel cross sections consistent

<table>
<thead>
<tr>
<th>( \sigma_{tot} [\text{nb}] )</th>
<th>( \sigma_{tot} )</th>
<th>( \Delta \sigma_{\text{stat}} )</th>
<th>( \Delta \sigma_{\text{syst}} )</th>
<th>( \Delta \sigma_{\text{lum}} )</th>
<th>( \Delta \sigma_{\text{acc}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^+ ) combined</td>
<td>6.041</td>
<td>0.016</td>
<td>0.077</td>
<td>0.205</td>
<td>0.096</td>
</tr>
<tr>
<td>( W^- ) combined</td>
<td>4.156</td>
<td>0.014</td>
<td>0.058</td>
<td>0.141</td>
<td>0.083</td>
</tr>
<tr>
<td>( W ) combined</td>
<td>10.197</td>
<td>0.021</td>
<td>0.127</td>
<td>0.347</td>
<td>0.165</td>
</tr>
<tr>
<td>( Z/\gamma^* ) combined</td>
<td>0.937</td>
<td>0.006</td>
<td>0.009</td>
<td>0.032</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Experimental precision of ~1%!
Limited by luminosity uncertainty!

Reference: paper to be published (soon)
Inclusive W and Z: $y/\eta$ - differential

- Differential measurement includes forward electrons for the first time!

Can be used to improve PDFs

Reference: paper to be published (soon)
W lepton universality

- W lepton universality measurement competitive with PDG world average: 2.4% w.r.t. 1.9%

Precise test of SM
**W/Z+jets**

**Motivation**
- Test of QCD and MC generators
- Important background for SM processes and BSM searches

V/jets
- **Selection**
  - 2 high $p_T$ leptons
    - $Z$ mass window, exactly 2 leptons of opposite charge
  - High $p_T$ Jet
    - anti-$k_T$, $R=0.4$, $p_T > 30$ GeV, $|\eta| < 2.8$
- **Differential cross sections**
  - $N_{\text{jet}}, N_{\text{jet}}/N_{\text{jet}}^{-1}, p_T, p_T, \text{leading jet}$

W+jets
- **Selection**
  - 1 high $p_T$ lepton
    - Isolated, second lepton veto
  - High $p_T$ Jet
    - anti-$k_T$, $R=0.4$, $p_T > 20$ GeV, $|\eta| < 2.8$
  - High missing $E_T$
    - Missing $E_T > 25$ GeV
- **Differential cross sections**
  - $N_{\text{jet}}, N_{\text{jet}}/N_{\text{jet}}^{-1}, H_T, p_T$ (leading jet, 2nd, 3rd and 4th leading jet)

Unfolding used to correct results back to parton level

Cross section ratio of W+jets/Z+jets

Reference: **paper to be published**

Reference: ATLAS-CONF-2011-042

Precision limited by jet energy scale uncertainty

Reference: ATLAS-CONF-2011-060

Reference: ATLAS-CONF-2011-060
Z+jets

Good agreement with MC predictions
Limited by systematics

Ratio W+1jet/Z+1jet

New analysis optimized for minimum uncertainty on ratio
Already reached systematic uncertainty below 5%
• Important background for both SM and BSM measurements
  – Higgs, SUSY etc.
• Non-abelian structure of the weak section of SM
  ➢ Triple Gauge Couplings (TGC)
• Sensitive to new physics via anomalous TGCs

• Cross section measurements done:
  – WW
  – WZ (aTGC limits!)
  – ZZ (aTGC limits!)
  – W+gamma/Z+gamma
• **Channels:**
  - $ee$, $\mu\mu$ or $e\mu$ + missing $E_T$

• **Selection:**
  - 2 high $p_T$ leptons
    - Opposite charge, isolated
    - $\mu$: $p_T > 20$ GeV
    - $e$: $E_T > 25$ ($20$) GeV leading(subleading)
  - Outside of Z mass window
    - $|m_{ll} - m_Z| > 15$ GeV
  - High missing $E_T$
    - $M_{T,\text{Rel}} > (40, 45, 25)$ GeV ($ee, \mu\mu, e\mu$)
  - Jet veto
    - $p_T > 30$ GeV, $|\eta| < 4.5$

• **Background estimation**
  - Top (data driven)
  - DY and Z+jets (MC+data driven)
  - $W$+jets (data driven)
  - Diboson (MC)

• **Cross section extracted via log likelihood method**

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1 $M_{T,\text{Rel}}$ is using topological information to improve rejection power

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Cross section consistent with theory prediction
Limited by systematic uncertainties

Reference: ATLAS-CONF-2011-110
WZ

Channels measured:
• eee, eεμ, εμμ or μμμ + ME_T

Event selection:
• 3 (or more) high pT leptons
  – isolated
  – W electron or trigger lepton: p_T > 20 GeV
  – Other leptons: p_T > 15 GeV
• Z candidate
  – |M_l-M_Z|<10GeV
• W candidate
  – Missing E_T>25GeV
  – M_T>20GeV

Background estimation
• W/Z+jets (data driven)
• ZZ (MC)
• Top (MC)
• W+γ (MC)

Cross section extracted via log likelihood method

Cross section consistent with theory prediction
Limited by statistics uncertainty

<table>
<thead>
<tr>
<th>Cross section</th>
<th>σ</th>
<th>Δσ_{stat}</th>
<th>Δσ_{syst}</th>
<th>Δσ_{lum}</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ^{tot}_{WZ}</td>
<td>pb</td>
<td>21.1</td>
<td>-3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>SM prediction</td>
<td>pb</td>
<td>17.2</td>
<td>-2.8</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

Reference: ATLAS-CONF-2011-099
**ZZ**

- First ATLAS ZZ measurement!
- Channels:  
  - $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$
- Selection:  
  - 4 high $p_T$ leptons  
    - Exactly 4 isolated leptons, 2 pairs of same flavour and opposite charge  
    - Leading $e$ ($\mu$): $p_T > 25$ (20) GeV  
    - Subleading lepton: $p_T > 15$ GeV  
  - $Z$ mass window  
    - $66 < M(l_1l_2 & l_3l_4) < 116$ GeV
- Very clean signal, low background  
  - $Z+X$ (misidentified jets)

**Cross section**

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>$\Delta \sigma_{\text{stat}}$</th>
<th>$\Delta \sigma_{\text{syst}}$</th>
<th>$\Delta \sigma_{\text{lum}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ZZ}^{\text{tot}}$ (pb)</td>
<td>8.4</td>
<td>$+2.7$</td>
<td>$+0.4$</td>
</tr>
<tr>
<td>SM pred. (NLO) (pb)</td>
<td>6.5</td>
<td>$-2.3$</td>
<td>$-0.7$</td>
</tr>
</tbody>
</table>

Reference: ATLAS-CONF-2011-107

Cross section consistent with theory prediction

Limited by statistics
W/Z+gamma

Selection:
• High $p_T$ lepton(s)
• Z candidate
  – Exactly two oppositely charged leptons
• W candidate
  – Exactly one lepton, $E_{T,\text{Miss}}>25\text{GeV}$, $m_T>40\text{ GeV}$
• High $p_T$ photon
  – $E_{T,\gamma}>15\text{ GeV}$, $\gamma$ isolation $<5\text{ GeV}$
  – $\Delta R(l,\gamma)>0.7$
  – Includes FSR and quark/gluon fragmentation contributions

Cross section
• Dominated by $\gamma$ efficiency uncertainty
• Cancels in ratio $\sigma_{W\gamma}/\sigma_{Z\gamma}$

Backgrounds
• $W(Z)+jets (\pi^0\rightarrow\gamma\gamma)$

<table>
<thead>
<tr>
<th>Cross section</th>
<th>$\sigma$</th>
<th>$\Delta\sigma_{\text{stat}}$</th>
<th>$\Delta\sigma_{\text{syst}}$</th>
<th>$\Delta\sigma_{\text{lum.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{W\gamma}$</td>
<td>pb</td>
<td>42.5</td>
<td>4.2</td>
<td>7.2</td>
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<tr>
<td>SM pred.</td>
<td>pb</td>
<td>42.1</td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>$\sigma_{Z\gamma}$</td>
<td>pb</td>
<td>6.4</td>
<td>1.2</td>
<td>1.6</td>
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<tr>
<td>SM pred.</td>
<td>pb</td>
<td>6.9</td>
<td>0.5</td>
<td></td>
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</tbody>
</table>


Cross section consistent with theory prediction
First analysis limited by syst, but can be improved
**Triple Gauge Couplings**

- Sensitivity to new physics!
- Possible vertices using a generalised Lagrangian
  - $WWZ$ (couplings: $\alpha_0 = g_1^Z$, $\kappa^Z$, $\lambda$) $\text{SM} = (1,1,0)$
  - $ZZZ$, $ZZ\gamma$ (couplings: $\alpha_0 = f_4^Z$, $f_4^\gamma$, $f_5^Z$, $f_5^\gamma$) $\text{SM} = (0,0,0,0)$
- Scale dependent formfactor with cutoff scale $\Lambda \sim O(2\text{TeV})$:
- ATLAS: cross sections as TGC limit input
- Tevatron: differential distributions as TGC limit input

\[
\alpha(\hat{s}) = \frac{\alpha(0)}{(1 - \frac{\hat{s}}{\Lambda^2})^2}
\]

**ATLAS limits consistent and competitive**

*Use of differential distributions: will increase sensitivity*
Summary

- Precise measurements of production cross sections of electroweak gauge bosons with data up to 1 fb^{-1}@ 7 TeV
- Results consistent with SM expectations
- Event properties well described by MC
- Analysis presented:
  - W/Z inclusive
    - Sensitive to PDFs,
    - Sensitive to W lepton flavour universality
  - W/Z+jets
    - Test of QCD/MC
  - Diboson
    - Sensitive to TGCs
- Many more analysis available but not shown

More Details on W/Z inclusive measurements and PDF sensitivity: In session 5A talk by S. Chouridou:
W and Z Production Measured Using the ATLAS Detector, and Impact on Partons Densities of the Proton
## List of available measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Z inclusive cross sections</td>
<td>Paper to be published</td>
</tr>
<tr>
<td>Differential Z distributions</td>
<td>arXiv:1107.2381v1</td>
</tr>
<tr>
<td>Differential W distributions</td>
<td>Paper to be published</td>
</tr>
<tr>
<td>Z-&gt;tautau cross section</td>
<td>Paper to be published</td>
</tr>
<tr>
<td>W-&gt;taunu cross section</td>
<td>Paper to be published</td>
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<tr>
<td>W+b cross section</td>
<td>Paper to be published</td>
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</tr>
<tr>
<td>Z+jets</td>
<td>ATLAS-CONF-2011-042</td>
</tr>
<tr>
<td>Ratio of the W+1jet to Z+1jet cross sections</td>
<td>Paper to be published</td>
</tr>
<tr>
<td>Wγ/Zγ cross section</td>
<td>arXiv:1104.5225</td>
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<tr>
<td>WW cross section</td>
<td>ATLAS-CONF-2011-110</td>
</tr>
<tr>
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<td>ATLAS-CONF-2011-099</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>ATLAS-CONF-2011-107</td>
</tr>
</tbody>
</table>
Event display

- Event display of a ZZ→eemumu candidate event (Run Number 182747, Event Number 63217197). One Z candidate has a mass of 85.9 GeV and a pt of 30.8 GeV and it is formed by two muons (in red) with \{pt, \eta, \phi\} of \{44.9 \text{ GeV}, 0.11, 0.69 \text{ rad}\} and \{44.5 \text{ GeV}, 0.53, -1.75 \text{ rad}\}, respectively. The other Z candidate has a mass of 85.5 GeV and a pt of 29.3 GeV, and it is formed by two electrons (in green) with \{pt, \eta, \phi\} of \{39.6 \text{ GeV}, 0.95, 1.19 \text{ rad}\} and \{42.2 \text{ GeV}, 1.85, -2.68 \text{ rad}\}, respectively. The four lepton system has a mass of 209.5 GeV and a pt of 4.6 GeV. Inner detector tracks with a transverse momentum pt larger than 1 GeV are displayed as blue helices.
W,Z inclusive

\[ \int L \, dt = 33 \, \text{pb}^{-1} \]

\[ \int L \, dt = 36 \, \text{pb}^{-1} \]

ATLAS Preliminary
Z $p_T$-differential

Reference: arXiv:1107.2381v1
**W/Z+jets**

**HT**: Scalar sum of p_T of jets passing the selection.
W/Z+jets

Z+jets

- Background estimation
  - QCD in ee+jet final state data driven (template fit)
  - Other backgrounds estimated via MC
- Unfolding
  - Bin-by-bin using ALPGEN
  - Systematics: use SHERPA instead of ALPGEN, use differences as error

W+jets

- Background estimation
  - QCD data driven (template fit for e and μ)
  - Other backgrounds estimated via MC
- Unfolding
  - Separate unfolding in $N_{jet}, p_T, H_T$
  - Systematics: use SHERPA instead of ALPGEN, use differences as error
Ratio of W+1jet/Z+1jet
• Definition of relative missing energy:

$$ E_{T, \text{Rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \times \sin(\Delta \phi_{\ell,j}) & \text{if } \Delta \phi < \pi/2 \\ E_T^{\text{miss}} & \text{if } \Delta \phi \geq \pi/2 \end{cases} $$
WZ background estimation

• Most important contribution: Z+jets (+ minor W+jets)
• Estimated from data besides $C_{\text{MET}}$
• Sample of Z+jet:
  – 2 leptons + 1 lepton-like jet passing all selection criteria "llj"
    • Exception: lepton-like jet fails electron ID / muon isolation:
      \[ N_{\text{bkg}} = N(llj) \cdot f(p_T) \cdot C_{\text{MET}} \]
  – Fake factor: probability to fail ID/isolation cut
    • Derived from Z + lepton-like jet sample (no MET, $M_T$ requirements)
      \[ f(p_T) = \frac{N(l, \text{MET} < 25\text{GeV})}{N(j, \text{MET} < 25\text{GeV})} \]
  – $C_{\text{MET}}$: Interpolation from low to high missing ET region, done via MC
    • Validated with dijet-events in data and MC
ZZ background estimation

- Estimate background from data
  - Dominant: one jet fakes a lepton
    \[ N(\text{bkg}) = N(\text{lllj}) \cdot f - N(\text{lljj}) \cdot f^2 - N(\text{ZZcandidates}) \]

- Fake factor \( f(p_T, \eta) \)
  - Ratio of probability for a jet to pass full lepton criteria over probability to pass lepton-like criteria
  - Derived from data sample in which true leptons are suppressed
  - Derived as single lepton quantity
  - Cross checked with MC

- \( N(\text{lllj}) \) (\( N(\text{lljj}) \)): number of events with 1 (2) lepton-like jets
  - Lepton-like jet: satisfies all criteria besides electron ID/ muon isolation

- To avoid double counting: substract \( N(\text{lljj}) \)