Standard Model ElectroWeak Physics at ATLAS

Pat Ward

16th November 2011
Outline

• Overview of ATLAS detector, data-taking and detector performance
  • Detector, trigger, data, luminosity measurement
  • Lepton reconstruction and performance

• Measurements with single W and Z bosons
  • Cross-section and cross-section ratio
  • Transverse momentum distributions, charge asymmetry

• Diboson production
  • $W\gamma$, $Z\gamma$, $WW$, $WZ$, $ZZ$ production cross-sections
  • Limits on anomalous triple gauge boson couplings

• Future Prospects

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Why SM EW Physics at LHC?

- Many SM parameters measured to high precision at LEP or Tevatron
- So why measure SM EW processes at LHC?
- Test SM in new high energy regime
- Improve measurements of some parameters
  - W mass and width
  - Triple gauge boson couplings
- Backgrounds to new physics – need to be understood
  - e.g. $H \rightarrow WW, ZZ$
- Discrepancies with SM may be first sign of new physics if this is not an ‘expected model’

<table>
<thead>
<tr>
<th>Value [PDG]</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ 91.1876 ± 0.0021 GeV</td>
<td>2 x 10^{-5}</td>
</tr>
<tr>
<td>$\Gamma_Z$ 2.4952 ± 0.0023 GeV</td>
<td>9 x 10^{-4}</td>
</tr>
<tr>
<td>$g_a$ -0.50123 ± 0.00026</td>
<td>5 x 10^{-4}</td>
</tr>
<tr>
<td>$g_v$ -0.03783 ± 0.0041</td>
<td>1%</td>
</tr>
<tr>
<td>$m_W$ 80.399 ± 0.023 GeV</td>
<td>3 x 10^{-4}</td>
</tr>
<tr>
<td>$\Gamma_W$ 2.085 ± 0.042 GeV</td>
<td>2%</td>
</tr>
<tr>
<td>$m_t$ 172.9 ± 0.6 ± 0.9 GeV</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Electroweak Bosons at LHC

- Cross-sections span several orders of magnitude:
  \( \sigma(W) \sim 15000 \times \sigma(ZZ) \)
- \( W \) and \( Z \) cross-sections calculated to NNLO
  - Important test of QCD
- Diboson cross-sections calculated to NLO
  - Gluon fusion contributes \(~3\%\) to WW and \(~6\%\) to ZZ
- Measured in leptonic decay channels: \( W \rightarrow l\nu, Z \rightarrow ll \)
  - Low branching ratios but experimentally clean signatures
ATLAS Detector

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Trigger

- \( W / Z \) leptonic final states selected with single-electron and single-muon triggers
- Nominal thresholds
  - \( e / \mu = 15 / 13 \) GeV (2010)
  - \( e / \mu = 20 / 18 \) GeV (early 2011)

![Diagram showing the ATLAS trigger system](image)
Data

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS recorded integrated luminosity</td>
<td>45 pb(^{-1})</td>
<td>5.25 fb(^{-1})</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>2.1 (\times 10^{32}) cm(^{-2}) s(^{-1})</td>
<td>3.65 (\times 10^{33}) cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>Mean interactions / bunch crossing</td>
<td>(~2)</td>
<td>6.3 / 11.6</td>
</tr>
</tbody>
</table>

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Electron Identification

- Match EM cluster to ID track
- **Loose** (jet rejection factor ~500):
  - EM shower shape in middle layer, hadronic leakage
- **Medium** (~5000):
  - +EM strip layer, track quality and track/cluster matching
- **Tight** (50000):
  - +E/\rho, TRT high threshold hits, tighter track cuts to remove photon conversions
- Measure reconstruction and ID efficiencies using tag-and-probe in \( W \rightarrow e\nu, Z \rightarrow ee, J/\psi \rightarrow ee \) events

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Muon Identification

- **`Combined’ muon:**
  - Match ID track with MS track
  - Combine parameters

- **`Segment-tagged’ muon:**
  - ID track matched to MS track segment
  - Used for regions with too few MS hits for momentum meas.

- Measure efficiency using **tag-and-probe** in $Z \rightarrow \mu\mu$ events
  - >96% and agrees with MC to better than 1%

- Momentum resolution measured from $Z \rightarrow \mu\mu$ mass distribution
  - Design: <3.5% ($p_T<$200GeV); <10% ($p_T<$1TeV)

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Jets and Missing ET

- Jets reconstructed from calorimeter clusters
- Anti-$k_T$ algorithm, $R=0.4$ or 0.6
- Jet energy scale (i.e. EM $\rightarrow$ hadronic) calibrated using MC
- Checked with data, e.g. track jets, jet-photon $p_T$ balance
- Missing transverse energy calculated using e/µ/jets plus unassociated calorimeter clusters in $|\eta| < 4.5$
  - Clusters calibrated as em or hadronic depending on topology
  - Correction for muon energy in calorimeter

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Luminosity Measurement

- Measure event rates in lumi. detectors
  - BCM: diamond sensors $z = \pm 1.84\text{m}$, $|\eta| \sim 4.2$
  - LUCID: Cerenkov tubes $z = \pm 17\text{m}$, $5.6 < |\eta| < 6.0$
- $L = \mu_{\text{vis}} n_b f_r / \sigma_{\text{vis}}$  \( \mu_{\text{vis}} \) = interaction rate / BX
- Calibrate rates (i.e. measure $\sigma_{\text{vis}}$) using van der Meer (beam separation) scans
- Separate beams in steps of known distance to measure beam profiles $\Sigma_x \Sigma_y$
  - Length scale checked using ATLAS primary vertex position
- $L = n_b f_r n_1 n_2 / 2\pi \Sigma_x \Sigma_y$
- Main systematic (3%) from measurement of beam currents
- Overall error on integrated $L$
  - 2010: 3.4%
  - 2011: 3.7%

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W and Z Boson Production

- Source of high-\(p_T\) electrons and muons for detector calibration and performance measurements
- Probes proton PDFs – particularly \(W^+/W^-\) ratio
- \(W/Z\) ratio can provide constraints on \(\Gamma_W\) and is sensitive to new physics
- Measure \(m(W)\)
  - Needs high statistics, precise measurement of \(W\) \(p_T\) distribution etc.
- Measured in leptonic decay channels: \(W \to l\nu, Z \to ll\)

W $\rightarrow$ lv Event Selection

- **Signature:** high $p_T$ isolated lepton and missing transverse energy
- **Electron**
  - Medium + b-layer hit
  - $E_T > 20$ GeV
  - $|\eta| < 2.47$ (excl. $1.37 – 1.52$)
  - Isolation: $E^{0.3} < E_{\text{max}}$
- **Muon**
  - $p_T > 20$ GeV
  - $|\eta| < 2.4$
  - $|Z_0^{PV}| < 1$ cm, ID hit req.
  - Isolation: $\Sigma p_T^{0.2} < 0.1 p_T^\mu$
- $E_T^{\text{Miss}} > 25$ GeV
- $m_T > 40$ GeV

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Z → ll Event Selection

- Opposite-sign same-flavour lepton pair
  - Lepton selection similar to W
- 66 GeV < m(ll) < 116 GeV
- Selected events in 33 / 36 pb⁻¹ (2010 data)

<table>
<thead>
<tr>
<th></th>
<th>W⁺</th>
<th>W⁻</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>77875</td>
<td>52856</td>
<td>9725</td>
</tr>
<tr>
<td>µ</td>
<td>84514</td>
<td>55234</td>
<td>11709</td>
</tr>
</tbody>
</table>
W / Z Cross-section Measurement

- **QCD background**
  - Jets faking electrons
  - Muons from heavy flavour decays
- Estimated using control samples in data
  - Invert electron ID cuts or muon isolation
- 2% – 5% in W channels
- < 2% in Z channels
- **Electroweak background**
  - $W \rightarrow \tau \nu$, $Z \rightarrow \tau \tau$, $t\bar{t}$, diboson
- Estimated from MC
  - 3% - 7% in W channels
  - ~0.5% in Z channels

- **Signal efficiencies and acceptances**
- Determined from MC
  - Scaling and smearing applied to MC to reproduce lepton efficiencies measured in data
  - Efficiencies ~70% (80%) for e (μ) channels
    - i.e. to correct to fiducial cross-section
  - Acceptances 45% – 50%
    - i.e. to obtain total cross-section from fiducial cross-section

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Fiducial Cross-sections

- Fiducial cross-sections measured in kinematic phase-space corresponding to experimental acceptance
  - No uncertainty from extrapolation
- Reasonable agreement with NNLO predictions
- Universality of PDFs and pQCD work up to kinematic range of W and Z at LHC
- Luminosity error dominates - unable to distinguish different PFD sets

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arXiv:1109.5141v2 [hep-ex]
Total Cross-sections

- Error from extrapolation to full phase space ~2% is bigger than experimental systematic
- Less able to discriminate between different PDFs

\[
\sigma_W^\text{tot} \cdot \text{BR}(W \rightarrow \ell \nu) \quad [\text{nb}]
\]

<table>
<thead>
<tr>
<th></th>
<th>sta</th>
<th>sys</th>
<th>lum</th>
<th>acc</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W^+)</td>
<td>6.048 ± 0.016 ± 0.072 ± 0.206 ± 0.096</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(W^-)</td>
<td>4.160 ± 0.014 ± 0.057 ± 0.141 ± 0.083</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(W^\pm)</td>
<td>10.207 ± 0.021 ± 0.121 ± 0.347 ± 0.164</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\sigma_{Z/\gamma^*}^\text{tot} \cdot \text{BR}(Z/\gamma^* \rightarrow \ell\ell) \quad [\text{nb}]
\]

\[
66 < m_{\ell\ell} < 116 \quad \text{GeV}
\]

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(Z/\gamma^*)</td>
<td>0.937 ± 0.006 ± 0.009 ± 0.032 ± 0.016</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[\int L \, dt = 33-36 \text{ pb}^{-1}\]

\[\sigma_Z^\text{tot} \cdot \text{BR}(Z/\gamma^* \rightarrow l^+l^-) \quad [\text{nb}]\]

68.3% CL ellipse area

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Energy Dependence

ATLAS results consistent with similar results from CMS [JHEP 10 (2011) 132]

LHCb measure forward W/Z

LHCb-CONF-2011-039

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W Charge Asymmetry

- Sensitive to valence quark distributions
  \[ A_{\ell}(\eta_\ell) = \frac{d\sigma_{W^+}/d\eta_\ell - d\sigma_{W^-}/d\eta_\ell}{d\sigma_{W^+}/d\eta_\ell + d\sigma_{W^-}/d\eta_\ell} , \]

- Asymmetry measured in \( p_{T,\ell} > 20 \text{ GeV}, p_{T,\nu} > 25 \text{ GeV}, m_T > 40 \text{ GeV} \)
  - Charge misID from like-sign Z events
  - 1% for ‘medium’ electrons
  - Negligible for muons

- NNLO predictions roughly compatible with measurements

\[ \int L \, dt = 33-36 \text{ pb}^{-1} \]

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Electron-muon Universality

- $R_W = \frac{\sigma_W(e)}{\sigma_W(\mu)}$
  $= \frac{\text{Br}(W \rightarrow ev)}{\text{Br}(W \rightarrow \mu \nu)}$
  $= 1.006 \pm 0.024$
- PDG: $1.017 \pm 0.019$
- CDF: $1.018 \pm 0.025$

- $R_Z = \frac{\sigma_Z(e)}{\sigma_Z(\mu)}$
  $= \frac{\text{Br}(Z \rightarrow ee)}{\text{Br}(Z \rightarrow \mu \mu)}$
  $= 1.018 \pm 0.031$
- PDG: $0.9991 \pm 0.0024$
W / Z Cross-section Ratio

- $W / Z$ cross-section ratio insensitive to PDFs if sea is flavour symmetric
- Hence all PDF sets give similar predictions
- Agreement with measurement supports assumption of flavour independent sea at high scales and $x \approx 0.01$
- Future: use to determine $\Gamma_W$?
- $$ R = \frac{\sigma(W) \Gamma(W \rightarrow l\nu)}{\sigma(Z) \Gamma(Z \rightarrow ll)} \frac{\Gamma_Z}{\Gamma_W} $$
- $\sigma(W)/\sigma(Z)$ calculated from couplings, PDFs
- $\Gamma_Z, \Gamma(Z \rightarrow ll)$ measured at LEP

Hence $R$ measures $Br(W \rightarrow l\nu)$
Using SM value of $\Gamma(W \rightarrow l\nu)$ can determine $\Gamma_W$
Method has been used by CDF to determine $\Gamma_W$ with precision of 42 MeV

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W $p_T$ Distribution

$\int L dt \approx 31 \text{ pb}^{-1}$

Data 2010, $\sqrt{s} = 7 \text{ TeV}$

at ATLAS

$\frac{1}{\sigma_{\text{tot}}} \left( \frac{d\sigma}{dp_T^W} \right) \left[ \text{GeV}^{-1} \right]$

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

Data

RESBOS

Data / RESBOS

$0 \leq 50 \leq 100 \leq 150 \leq 200 \leq 250 \leq 300$

$p_T^W \text{ [GeV]}$

arXiv:1108.6308 [hep-ex]
Z $p_T$ Distribution

$1/\sigma_{\text{fid}} \cdot \frac{d\sigma}{dp_T^Z} [1/\text{GeV}]$

$\int L \, dt = 35-40 \, \text{pb}^{-1}$

**ATLAS**

**Combined ee+\mu\mu**

- Data 2010
- RESBOS
- FEWZ $O(\alpha_s^2)$
- PYTHIA

$|\eta^l| < 2.4$
$p_T^l > 20 \, \text{GeV}$
$66 \, \text{GeV} < m_{ll} < 116 \, \text{GeV}$

Data (Prediction) / RESBOS

**Combined ee+\mu\mu**

- Data 2010
- RESBOS
- PYTHIA
- MC@NLO
- POWHEG
- ALPGEN
- SHERPA

$|\eta^l| < 2.4$
$p_T^l > 20 \, \text{GeV}$
$66 \, \text{GeV} < m_{ll} < 116 \, \text{GeV}$
Diboson Production

- Measurements of diboson production ($W\gamma$, $Z\gamma$, $WW$, $WZ$, $ZZ$) test gauge structure of SM
- s-channel diagram contains triple gauge boson coupling (TGC) vertex
- TGC predicted by SM
  - Zero for 3 neutral bosons
  - Measured at LEP and Tevatron
- Non-SM TGC values typically increase cross-section at high diboson mass and transverse momentum

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Charged TGCs

• Effective Lagrangian for WWV vertex ($V = Z, \gamma$), considering only terms that conserve C and P separately:

$$L/g_{WWV} = ig_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i\kappa^V W_{\mu\nu} W^\mu V^\nu + \frac{\lambda^V}{M_W^2} W_{\rho\mu}^* W_{\nu}^\mu V^{\nu\rho}$$

• 3 dimensionless coupling parameters for each of WWZ, WWγ: $g_1^V, \kappa^V, \lambda^V$
• In SM, $g_1^V = \kappa^V = 1; \lambda^V = 0$
• Hence define anomalous couplings: $\Delta g_1^V = g_1^V - 1; \Delta \kappa^V = \kappa^V - 1; \lambda^V$
• WW production measures mixture of WWZ and WWγ
• WZ production measures WWZ vertex only
• To avoid unitarity violation at high energies, may use form factor, e.g.

$$\Delta \kappa(s') = \Delta \kappa / (1 + s' / \Lambda^2)^n$$

$s' = \text{parton cm energy}$

• $\Lambda = \text{energy scale of new physics}$
• ATLAS limits from WZ use $\Lambda=2 \text{ TeV}, n=2$ and $\Lambda = \infty$
Neutral TGCs

- For on-shell ZZ production, effective Lagrangian for ZZV vertex is:

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

- 2 dimensionless parameters for each of ZZZ,ZZ\gamma: \( f_4^V, f_5^V \)
- \( f_4^V \) violates CP, \( f_5^V \) violates P
- In SM all \( f = 0 \)
- Use form-factor as for charged TGCs to prevent unitarity violation at high energy
- ATLAS ZZ limits use \( n=3, \Lambda=2 \) TeV and \( \Lambda = \infty \)
Wy and Zy

Wy selection:
- Lepton with $p_T > 20$ GeV
- $E_T^{\text{Miss}} > 25$ GeV
- $m_T(l,\nu) > 40$ GeV

Zy selection:
- Opposite-sign same-flavour lepton pair
- $m(ll) > 40$ GeV

Wy and Zy:
- Photon $E_T > 15$ GeV
- Isolated: $E_T^{0.4} < 5$ GeV
- $\Delta R(l,\gamma) > 0.7$ (suppress FSR)
Wy and Zy

- Main background W+jets
  - Estimated from data
- Results
  - $p_T(\gamma) > 15$ GeV
  - $\Delta R(l,\gamma) > 0.7$
  - $\varepsilon_{h^p} < 0.5$
- Main systematic photon efficiency (~10%)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$(meas) / pb</th>
<th>$\sigma$ (SM) / pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow l\nu\gamma$</td>
<td>$36.0 \pm 3.6 \pm 6.2 \pm 1.2$</td>
<td>$36.0 \pm 2.3$</td>
</tr>
<tr>
<td>$pp \rightarrow l^\pm l^\mp\gamma$</td>
<td>$6.5 \pm 1.2 \pm 1.7 \pm 0.2$</td>
<td>$6.9 \pm 0.5$</td>
</tr>
</tbody>
</table>

- Good agreement with SM

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Wγ / Zγ Ratio

- Cross-section ratio is test of WWγ TGC
- Measured ratio in good agreement with SM
- Future: limits on WWγ, ZZγ, Zγγ TGC

 CMS: PLB 701 (2011) 535
**WW → ℓνℓν**

- **Signature:** 2 high-\(p_T\) isolated leptons + MET
- **Selection:**
  - Exactly 2 leptons, opposite sign, \(p_T > 20\) GeV (\(W,Wγ,WW,ZZ\))
    - Leading \(e\) \(p_T > 25\) GeV
    - Trigger match
  - **Z veto** \((Z)\)
    - \(|m(\ell\ell) − m(Z)| > 15\) GeV
    - \(m(\ell\ell) > 15\) GeV, \(m(\ell e\mu) > 10\) GeV
  - **MET** \((Z)\)
    - \(E_{T,\text{Rel}}^{\text{Miss}} > (45,40,20)\) GeV
      (\(\mu\mu,ee,e\mu\))
  - **Jet veto** \((Z,\text{ttbar})\)
    - No jet (anti-\(k_T\), \(ΔR=0.4\)) with \(p_T > 30\) GeV, \(|η| < 4.5\)
• Background estimation:
  • $t\bar{t}$: from events in data with $\geq 2$ jets, scaled by $0 / \geq 2$ ratio in top MC
  • W+jets:
    • Data control sample with lepton + `lepton-like jet’
    • Scale by $f(p_T) = P(l)/P(j)$
    • $f$ measured in dijet sample
  • Otherwise MC
Observed events: 414

Total background: 169.8 ± 6.4 ± 27.1

Expected WW: 232.4 ± 0.9 ± 21.5

Main systematics:
- Lepton reconstruction, identification and isolation efficiencies
- Uncertainty in $E_T^{\text{miss}}$
- Jet veto

Total cross-section: 48.2 ± 4.0 ± 6.4 ± 1.8 pb

SM: 46 ± 3 pb

Good agreement with SM
WZ $\rightarrow$ lvll

- Signature: 3 high-$p_T$ isolated leptons + MET
- Selection:
  - 3 leptons $p_T > 15$ GeV
  - $|m(ll) - m(Z)| < 10$ GeV
  - 3rd lepton ‘tight’, $p_T > 20$ GeV
  - MET $> 25$ GeV
  - $m_T(W) > 20$ GeV
  - Trigger match with $p_T(e,\mu) > (25,20)$ GeV
- Background
  - Z+jets, ttbar from data
- Efficiencies, acceptances
  - MC with data corrections
Observed events 71
Total background $10.5 \pm 0.8^{+2.9}_{-2.1}$
Expected WZ $49.1 \pm 0.4 \pm 3.0$

Total cross-section $21.1^{+3.1}_{-2.8} \pm 1.2^{+0.9}_{-0.8}$ pb
SM $17.3^{+1.3}_{-0.8}$ pb
Charged TGC from WZ Production

- Limits from total event yield; profile likelihood ratio as test statistic
- Reweight fully-simulated events (MC@NLO) to find expected numbers for different coupling values
- Find range of coupling for which 5% of pseudo-experiments give smaller value of likelihood ratio than data
- Limits assume other couplings = SM values

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• Signature: 4 high-\(p_T\), isolated leptons

• Very low background

• Selection:
  • 4 leptons, \(p_T > 15\text{ GeV}, |\eta| < 2.5\) (\(\mu\)) / 2.47 (\(e\))
  • Isolation: \(\Sigma p_T^{0.2} < 0.15\ p_T^l\)
  • One with \(p_T > 20\) (\(\mu\)) / 25 (\(e\)) \(\text{GeV}\) trigger-matched
  • Two opposite-sign same-flavour pairs in \(|m(ll) - m(Z)| < 25\ \text{GeV}\)

• Background (\(Z+\text{jets}, \text{ttbar}\))
  • Data-driven – using events with `lepton-like jets’

\[\text{arXiv:1110.5016 [hep-ex]}\]
<table>
<thead>
<tr>
<th>Event Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>12</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.3 \pm 0.3$ $^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>Expected ZZ signal</td>
<td>$8.9 \pm 0.1 \pm 0.3$</td>
</tr>
<tr>
<td>Total cross-section</td>
<td>$8.5 \pm 2.7 \pm 0.4 \pm 0.3 \pm 0.3$ pb</td>
</tr>
<tr>
<td>SM</td>
<td>6.5 pb</td>
</tr>
</tbody>
</table>

- 4-muon channel
  - Observe 8 events
  - Expect 3.3 $^{+0.4}_{-0.3}$
  - Prob = 3.2%

Good agreement with SM
Neutral TGCs

- Limits from total event yield
- Reweight events generated with SHERPA to determine expected yield for different couplings
- Determine limits from maximum profile likelihood fit
- Assume couplings real, and others are SM values
- Limits dominated by statistics, but are tighter than LEP, Tevatron

\begin{center}
\begin{tabular}{lccccc}
\hline
\Lambda & \( f_{40} \) & \( f_{40}^{Z} \) & \( f_{50}^{Y} \) & \( f_{50}^{Z} \) \\
2 \text{ TeV} & \([-0.15, 0.15]\) & \([-0.12, 0.12]\) & \([-0.15, 0.15]\) & \([-0.13, 0.13]\) \\
\infty & \([-0.08, 0.08]\) & \([-0.07, 0.07]\) & \([-0.08, 0.08]\) & \([-0.07, 0.07]\) \\
\hline
\end{tabular}
\end{center}
Future Prospects

- ATLAS has now recorded >5 fb\(^{-1}\) of 7 TeV pp collision data
  - Factor 4-5 increase in diboson statistics (statistically limited)
  - Improved understanding of systematics - more detailed studies of W/Z
- Many updates to full dataset are planned for Moriond
- Add extra decay channels, e.g. ZZ \(\rightarrow\) llvv
  - Branching ratio 6 times ZZ \(\rightarrow\) 4l, but higher background
- Use kinematic information to improve limits on anomalous couplings from WZ and ZZ production
  - Expect 20 – 40% improvements compared with using total yield, depending on coupling
- Anomalous coupling limits from WW, W\(\gamma\), Z\(\gamma\) and combinations where appropriate
Future Prospects

- Work in progress on other SM EW measurements
- Measurement of $\sin^2 \theta_W^{\text{eff}}$
  - Interference of vector and axial-vector couplings leads to asymmetry in polar angle of lepton wrt initial quark direction in $q \bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-$
  - Asymmetry used to measure $\sin^2 \theta_W^{\text{eff}}$ at LEP, Tevatron
    - Precision $\sim 0.1\%$
  - In pp collisions can only determine $q / \bar{q}$ statistically
  - Recent results from CMS using $Z \rightarrow \mu\mu$ in 1.1 fb$^{-1}$ data [arXiv:1110.2682]:
    - $\sin^2 \theta_W^{\text{eff}} = 0.2287 \pm 0.0020 \pm 0.0025$
    - Precision $\sim 1\%$
- Measurement of W mass
  - Needs detailed understanding of energy scales
Summary

- ATLAS has collected more than 5fb$^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV
- Detector performance has been excellent, and many SM measurements have been made:
  - W/Z production cross-sections – limited by systematics with only a fraction of the data
  - W/Z differential cross-sections, W/Z+jets
  - Diboson ($W\gamma$, $Z\gamma$, $WW$, $WZ$, $ZZ$) production cross-sections
  - Limits on nTGCs already tighter than LEP / Tevatron with only 1fb$^{-1}$ data
- No deviations from SM expectations yet
- Work in progress on many measurements, e.g.
  - More precise diboson measurements and TGC limits
  - Z asymmetry and $\sin^2\theta_W^{\text{eff}}$
  - W boson mass

16th November 2011
C. P. Ward
Backup
## Data Quality

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>LAr EM, LAr HAD, LAr FWD, Tile</td>
<td>MDT, RPC, CSC, TGC</td>
<td>Solenoid, Toroid</td>
</tr>
<tr>
<td>100</td>
<td>98.4, 99.3, 99.4, 98.3</td>
<td>99.8, 99.5, 99.8, 99.9</td>
<td>99.7, 99.5</td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and August 24th (in %), after the summer 2011 reprocessing campaign.

### 2011

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>LAr EM, LAr HAD, LAr FWD, Tile</td>
<td>MDT, RPC, CSC, TGC</td>
</tr>
<tr>
<td>99.1</td>
<td>90.7, 96.6, 97.8, 100</td>
<td>99.9, 99.8, 96.2, 99.8</td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.
Inner Detector Tracking Performance

Excellent alignment

Primary vertex resolution

Pile-up performance

16th November 2011

C. P. Ward
Cross-sections measured in \( \tau \) channels agree well with those measured in e/\( \mu \) channels.
$W + \text{jets}$

$\sigma(W + \geq N_{\text{jet}} \text{ jets}) \text{ [pb]}$

$\int L dt = 33 \text{ pb}^{-1}$

$\frac{\text{Theory/Data}}{\text{Inclusive Jet Multiplicity, } N_{\text{jet}}}$

$W \rightarrow e\nu + \text{jets}$

- Data 2010, $s = 7 \text{ TeV}$
- ALPGEN
- SHERPA
- PYTHIA
- BLACKHAT-SHERPA
- MCFM

$ATLAS$ Preliminary

16th November 2011  C. P. Ward
Z + jets

arXiv:1111.2690 [hep-ex]
<table>
<thead>
<tr>
<th>Final State</th>
<th>$e^+e^-E_T^{\text{miss}}$</th>
<th>$\mu^+\mu^-E_T^{\text{miss}}$</th>
<th>$e^\pm\mu^\mp E_T^{\text{miss}}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Events</td>
<td>74</td>
<td>97</td>
<td>243</td>
<td>414</td>
</tr>
<tr>
<td>Background estimations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top (data-driven)</td>
<td>$9.5\pm0.3\pm3.6$</td>
<td>$12.3\pm0.4\pm4.7$</td>
<td>$36.8\pm1.3\pm14.0$</td>
<td>$58.6\pm2.1\pm22.3$</td>
</tr>
<tr>
<td>W+jets (data-driven)</td>
<td>$5.3\pm0.4\pm1.7$</td>
<td>$12.4\pm2.9\pm5.2$</td>
<td>$32.9\pm3.8\pm9.2$</td>
<td>$50.5\pm4.8\pm14.7$</td>
</tr>
<tr>
<td>Drell-Yan (MC/data-driven)</td>
<td>$18.7\pm1.9\pm1.9$</td>
<td>$19.2\pm1.7\pm2.1$</td>
<td>$16.0\pm2.8\pm1.7$</td>
<td>$54.0\pm3.7\pm4.5$</td>
</tr>
<tr>
<td>Other dibosons (MC)</td>
<td>$0.9\pm0.1\pm0.1$</td>
<td>$2.4\pm0.2\pm0.3$</td>
<td>$3.4\pm0.3\pm0.4$</td>
<td>$6.8\pm0.4\pm0.8$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$34.4\pm2.0\pm4.4$</td>
<td>$46.3\pm3.4\pm7.3$</td>
<td>$89.1\pm4.9\pm16.8$</td>
<td>$169.8\pm6.4\pm27.1$</td>
</tr>
<tr>
<td>Expected WW Signal</td>
<td>$29.5\pm0.3\pm3.0$</td>
<td>$52.5\pm0.4\pm4.9$</td>
<td>$150.5\pm0.7\pm13.4$</td>
<td>$232.4\pm0.9\pm21.5$</td>
</tr>
<tr>
<td>Significance ($S/\sqrt{B}$)</td>
<td>5.0</td>
<td>7.7</td>
<td>15.9</td>
<td>17.8</td>
</tr>
<tr>
<td>Final State</td>
<td>$eee + E_T^{\text{miss}}$</td>
<td>$ee\mu + E_T^{\text{miss}}$</td>
<td>$e\mu\mu + E_T^{\text{miss}}$</td>
<td>$\mu\mu\mu + E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>--------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Observed</td>
<td>11</td>
<td>9</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.34±0.07</td>
<td>1.03±0.13</td>
<td>0.82±0.12</td>
<td>1.40±0.15</td>
</tr>
<tr>
<td>$W/Z+$jets</td>
<td>2.03±0.38</td>
<td>0.64±0.18</td>
<td>2.03±0.38</td>
<td>0.44±0.15</td>
</tr>
<tr>
<td>Top</td>
<td>0.26±0.10</td>
<td>0.31±0.09</td>
<td>0.41±0.12</td>
<td>0.60±0.15</td>
</tr>
<tr>
<td>$W/Z + \gamma $</td>
<td>0.49±0.28</td>
<td>–</td>
<td>0.56±0.39</td>
<td>–</td>
</tr>
<tr>
<td>Total Background</td>
<td>3.08±0.49</td>
<td>1.98±0.24</td>
<td>3.82±0.56</td>
<td>2.44±0.21</td>
</tr>
<tr>
<td>Expected Signal</td>
<td>7.55±0.17</td>
<td>11.27±0.20</td>
<td>12.12±0.22</td>
<td>18.16±0.27</td>
</tr>
<tr>
<td>Expected S/B</td>
<td>2.5</td>
<td>5.7</td>
<td>3.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Channel</td>
<td>Observed</td>
<td>BG (data-driven)</td>
<td>Expected ZZ</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
<td>-------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-e^+e^-$</td>
<td>2</td>
<td>$0.01^{+0.03+0.05}_{-0.01-0.01}$</td>
<td>$1.53\pm0.03\pm0.10$</td>
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<tr>
<td>$\mu^+\mu^-\mu^+\mu^-$</td>
<td>8</td>
<td>$0.3 \pm 0.3 \pm 0.3$</td>
<td>$3.03\pm0.04\pm0.06$</td>
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<tr>
<td>$e^+e^-\mu^+\mu^-$</td>
<td>2</td>
<td>$&lt;0.01^{+0.03}_{-0.01}$</td>
<td>$4.37\pm0.04\pm0.14$</td>
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<tr>
<td>$\ell^+\ell^-\ell^+\ell^-$</td>
<td>12</td>
<td>$0.3 \pm 0.3^{+0.4}_{-0.3}$</td>
<td>$8.9\pm0.1\pm0.3$</td>
<td></td>
</tr>
</tbody>
</table>