Precision measurements and searches with single and multiple gauge bosons with the ATLAS detector

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On behalf of the ATLAS Collaboration

5th International Conference on New Frontiers in Physics, Kolumbari, Greece
July 9, 2016
A lot of nice ATLAS SM results using Run1/Run2 data were currently produced.

Precision increased up to comparisons with NNLO theory predictions.
**Motivation**

- Two main goals of Standard Model (SM) measurements in ATLAS are: to test theory with high precision and to find signs of new physics.

**More details:**

Measurement of integrated, differential cross sections and different angular distributions
- to prove validity of Standard Model at the TeV scale;
- to compare with theory predictions of higher order QCD and QED effects;
- to probe the proton structure;
- to understand irreducible diboson backgrounds into Higgs and exotic analyses.

Extrapolation of self-coupling structure of gauge bosons
- will improve our understanding of electroweak symmetry breaking and unitarity;
- intersect with determination of Higgs couplings;
- indicate “new physics” if anomalous triple/quartic gauge couplings are present.
Cross-section measurement in a nutshell

Number of observed events in fiducial region

Number of background (MC simulation / data-driven)

\[ \sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times C \times \int Ldt} \]

Signal acceptance on generator level in fiducial region

Signal efficiency on detector level

\[ A = \frac{N_{fid}}{N_{gen}} \]

\[ C = \frac{N_{sel}}{N_{fid}} \]

Differential cross section: Study of unfolded differential distributions and probe high momentum events for anomalous TGC’s and QGC’s
Single gauge boson measurements
Inclusive $W$ and $Z @ 13$ TeV

Starting point:
Data: $L=81$ pb$^{-1} \pm 2.1\%$ (50 ns)
MC signal: Powheg+Pythia8; Main bkgs: jet-jet, $Z/W$ inc.

Selection for fiducial region:
$W \rightarrow e\nu/\mu\nu$ \quad $m_T(W) > 50$ GeV

$Z \rightarrow e\nu/\mu\nu$ \quad $66$ GeV $< m_{ll} < 116$ GeV

$P_T(l,\nu) > 25$ GeV \quad $|\eta|<2.5$

Cross section measurement results:

- Good agreement with NNLO QCD and NLO EW prediction
  (several different PDF sets were considered)
- Dominant uncertainties are from Luminosity, JES and
  multijet bkg.

arXiv:1603.09222
Cross section ratios:

<table>
<thead>
<tr>
<th></th>
<th>Measured ratio</th>
<th>Predicted ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+/W^-$</td>
<td>$1.295 \pm 0.003 \pm 0.010$</td>
<td>$1.30 \pm 0.01$</td>
</tr>
<tr>
<td>$W^\pm/Z$</td>
<td>$10.31 \pm 0.04 \pm 0.20$</td>
<td>$10.54 \pm 0.12$</td>
</tr>
</tbody>
</table>

- Some uncertainties are partially cancelled in ratios (lumi, lepton ID and trigger)
- $W^+/W^-$: better agreement with CT14nnlo and MMHT14nnlo (precision: ~1%: just uncorrelated part of multijet bkg uncertainty)
- $W/Z$: good agreement for all PDF sets (precision: ~2%: multijet bkg, JES, JER error).
  - To improve PDFs – it needs higher precision.

Some sensitive to low-\(x\) u-v d quark PDFs

Some sensitive to s quark PDFs

\(R_{W^+/W^-} = \frac{\sigma_{W^+}^{\text{fid}}}{\sigma_{W^-}^{\text{fid}}}\)

\(R_{W/Z} = \frac{\sigma_{W}^{\text{fid}}}{\sigma_{Z}^{\text{fid}}}\)
Angular coefficients in Z boson events @ 8 TeV

Motivation:
- Measurement of production dynamics through a spin 1 Z via spin correlation between initial and final state partons.
- Use Collins-Soper (CS) reference frame: it defines lepton $\theta$ and $\phi$. Coefficients can be expressed as a function of $\theta$ and $\phi$:

$$\langle \frac{1}{2} (1 - 3 \cos^2 \theta) \rangle = \frac{3}{20} (A_0 - \frac{2}{3}); \quad \langle \sin 2\theta \cos \phi \rangle = \frac{1}{5} A_1; \quad \langle \sin^2 \theta \cos 2\phi \rangle = \frac{1}{10} A_2;$$

$$\langle \sin \theta \cos \phi \rangle = \frac{1}{4} A_3; \quad \langle \cos \theta \rangle = \frac{1}{4} A_4; \quad \langle \sin^2 \theta \sin 2\phi \rangle = \frac{1}{5} A_5;$$

$$\langle \sin 2\theta \sin \phi \rangle = \frac{1}{5} A_6; \quad \langle \sin \theta \sin \phi \rangle = \frac{1}{4} A_7.$$

Selection for fiducial region:
$Z \rightarrow ee/\mu\mu \quad 80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$
Central-central channel: $p_T(l) > 25 \text{ GeV} \quad |\eta_l| < 2.4 \quad \text{OR}$
Central-forward channel: $p_T(e) > 20 \text{ GeV} \quad 2.5 < |\eta_e| < 4.9$

Result:
Coefficients $A_{0-7}$ and comparison with theory:
- In general comparison with Powheg+MINLO and DYNNLO show good agreement with data.
- $A_0$-$A_2$ confirms Lam-Tung breaking @ higher orders than NLO → very sensitive probe of higher order QCD corrections!

Deviations are due to higher-order QCD effects
Multiple gauge boson measurements
WZ @ 8 TeV

**Starting point:**
Data: \(L = 20.3\ \text{fb}^{-1} \pm 1.9\%\)
MC signal: Powheg+Pythia8; Main bkgs: misID leptons, ZZ (~20% total).

**Selection for fiducial region:**
\(W^\pm Z \rightarrow l^\pm v l^\mp l^\mp (l=e/\mu):\) On shell \(Z\) – \(ll\) invariant mass within 10 GeV near \(Z\) peak;
\(p_T(l) > 15(20)\ \text{GeV}\) for lepton from \(Z(W)\), lepton \(|\eta|<2.5\); \(m_T(l\nu) > 30\ \text{GeV}\)

**Measurements of:**
- Integrated \(\sigma\), differential \(\sigma\) distributions, \(\sigma(W^+Z)/\sigma(W^-Z)\) and limits set on aTGC’s.
- Search for VBS WZ and limits set on aQGC’s in VBS phase space.

**Graphs:**
- Good overall agreement between data and predictions.
- Fair agreement, NNLO can help
**Systematics:**

- Statistical and systematic uncertainties for the ratio $\sigma(W^+Z)/\sigma(W^-Z)$ is roughly on the same order as for integrated $\sigma$.
- Uncertainty dominated by electron Id. efficiency, luminosity, muon reco. efficiency and knowledge of mis-id background.
- Dominant theory uncertainty due to QCD scale uncertainty.

\[
\sigma_{W\pm Z}^{\text{tot}} = 24.3 \pm 0.6\,\text{(stat)} \pm 0.6\,(\text{sys}) \pm 0.4\,(\text{th}) \pm 0.5\,(\text{lumi}) \,\text{pb} \\
\sigma_{W\pm Z}^{\text{theory}} = 21.0 \pm 1.6 \,\text{pb}
\]

**NNLO predictions can make agreement better.**
Starting point:
Data: $L = 3.2 \text{ fb}^{-1} \pm 2.1\%$
MC signal: Powheg+Pythia8; Main bkgs: misID leptons, ZZ ($\sim20\%$ total).

Selection for fiducial region:
$W^\pm Z \rightarrow l^\pm v l^\pm$ ($l = e/\mu$): On shell $Z - ll$ invariant mass within 10 GeV near $Z$ peak;
$p_T(l) > 15 (20)$ GeV for lepton from $Z(W)$, lepton $|\eta| < 2.5$; $m_{T(lv)} > 30$ GeV

Measurements of:
- Integrated $\sigma$, differential $\sigma$ vs jet multiplicity and $\sigma(W^+Z)/\sigma(W-Z)$.

$\sigma_{W^\pm Z}^{\text{tot}} = 50.6 \pm 2.6 \text{ (stat.)} \pm 2.0 \text{ (sys.)} \pm 0.9 \text{ (th.)} \pm 1.2 \text{ (lumi.) pb}$

$\sigma_{W^\pm Z}^{\text{theory}} = 48.2^{+1.1}_{-1.0} \text{ (scale) pb}$

Comparison of data, NLO and NNLO predictions

NLO and NNLO are quite different

Good overall agreement between data and predictions.
Systematics:

- Statistical and systematic uncertainties for the $\sigma(W^+Z)/\sigma(W^-Z)$ is roughly on the same order as for integrated $\sigma$.
- Uncertainty dominated by electron Id. efficiency, luminosity, muon reco. efficiency and knowledge of mis-id background.
- Dominant theory uncertainty due to QCD scale uncertainty.

$$\frac{\sigma_{\text{fid.}}^{W^+Z \rightarrow l'\nu ll}}{\sigma_{\text{fid.}}^{W^-Z \rightarrow l'\nu ll}} = 1.39 \pm 0.14 \text{ (stat.)} \pm 0.03 \text{ (sys.)}$$
Starting point:
Data: $L = 3.2 \, fb^{-1} \pm 2.1\%$
MC signal: Powheg+Pythia8; Main bkgs: $t\bar{t}Z$, non-hadronic triboson ($\sim 1\%$ total).

Selection for fiducial region:
$ZZ \rightarrow 4l(4l=4e/4\mu/2e2\mu)$: for each $Z - 66 \, GeV < m_{ll} < 116 \, GeV$;
$p_T(l) > 20 \, GeV$, lepton $|\eta| < 2.7$

Measurements of:
- Integrated $\sigma$

$$\sigma_{ZZ}^{tot} = 16.7^{+2.2}_{-2.0}^{(stat.)} +0.9_{-0.7}^{(syst.)} +1.0_{-0.7}^{(lumi.)} \, pb$$

$NNLO$ prediction:

$$\sigma_{ZZ}^{th} = 15.6^{+0.4}_{-0.4} \, pb$$

Measurement is statistically dominated.
Starting point:
Data: $L=20.3\text{ fb}^{-1} \pm 1.9\%$
MC signal: Powheg+Pythia8; Main bkgs: top quark, W+jets, DY (~25% total).

Selection for fiducial region:
$W^+W^-\rightarrow ll\nu\nu(l=e/\mu)$: $p_T(\nu\nu)>20(45)$ GeV for $e\mu(ee/\mu\mu)$; $|m_Z-m_{ll}|>15$ GeV for $ee/\mu\mu$ events. $p_T(l)>25(20)$ GeV for (sub)leading lepton, lepton $|\eta|<2.4(2.47)$ for $\mu(e)$. Jet veto applied.

Measurements of:
- Integrated $\sigma$, differential $\sigma$ distributions and limits set on aTGC’s.

$$\sigma_{\text{tot}}(pp \rightarrow WW) = 71.1\pm1.1(\text{stat})^{+5.7}_{-5.0}(\text{syst})\pm1.4(\text{lumi})\text{ pb} \quad \sigma(\text{NNLO}_{\text{tot}})_{\text{th}} = 63.2^{+1.6}_{-1.4}(\text{scale})\pm1.2(\text{PDF})$$

Measurement is in agreement with NNLO theory (integrated and differential).
Main systematics from JES, multijet bkg, jet veto, soft QCD.
**Starting point:**
Data: $L = 20.3 \text{ fb}^{-1} \pm 1.9\%$
MC signal: Herwig++/FPMC; Main bkg: $Z/\gamma^* \rightarrow \tau \tau, \text{VV}$

**Event selection:**
$\gamma\gamma \rightarrow W^+W^- \rightarrow e\mu\nu\nu$: $p_T(e\mu)>30 \text{ GeV}; m_{ll}>20 \text{ GeV};$
$p_T(l)>25(20) \text{ GeV}$ for leading(subleading) lepton, $|\eta_l|<2.5(2.47)$ for $\mu(e);$  
Exclusivity selection: no extra tracks within $\Delta z=1 \text{ mm}$ from $z$ average of 2 selected leptons.

**Measurements of:**
- Integrated $\sigma$ and limits set on aQGC’s.

Measurement is in agreement with theory, uncertainty is statistically dominated.
Starting point:
Data: L=20.3 fb\(^{-1}\) ± 1.9%
MC signal: Sherpa; Main bkg: Z+jets - for ll\(\gamma\)(~15%), γ+jets, Wγ, W(\(\ell\ell\)γ) – for \(\nu\nu\gamma\)(~40-60%).

Selection for fiducial region:
\(Z\gamma\rightarrow ll\gamma(l=e/\mu)\): \(p_T(l)>25\) GeV, \(|\eta_l|<2.47; m_{ll}>40\) GeV; \(E_T(\gamma)>15\) GeV, \(|\eta_\gamma|<2.37\).
\(Z\gamma\rightarrow \nu\nu\gamma\): \(E_T(\gamma)>130\) GeV, \(|\eta_\gamma|<2.37; p_T(\nu\nu)>100\) GeV; \(\Delta\phi[\gamma, p_T(\nu\nu)]>\pi/2\).

Measurements of:
- Integrated σ, differential σ distributions and limits set on aTGC's.
- Measured cross section agrees well with SM within uncertainties
- Main uncertainty on: lepton ISO (ll\(\gamma\)), JES, lumi, γ-ISO (\(\nu\nu\gamma\))
Starting point:
Data: L=20.3 fb\(^{-1}\) ± 1.9%
MC signal: Sherpa; Main bkgs: Zjets - for \(\ell\ell\gamma\) (~15-30%), \(\gamma+jets\), W(eνγ) – for ννγγ (~50-60%).

Selection for fiducial region:
\(Z\gamma\gamma \rightarrow \ell\ell\gamma\gamma(\ell=e/\mu): p_T(\ell)>25\text{ GeV, } |\eta_{\ell}|<2.47; m_{\ell\ell}>40\text{ GeV, } E_T(\gamma)>15\text{ GeV, } |\eta_\gamma|<2.37.
\(Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma: E_T(\gamma)>22\text{ GeV, } |\eta_\gamma|<2.37; p_T(\nu\nu)>110\text{ GeV, } \Delta\phi[\gamma\gamma, \nu\nu]>5\pi/6\)

Measurements of:
- Integrated \(\sigma\) and limits set on aQGC’s.

- Measured cross section agrees with SM within uncertainties
- Main uncertainty on: lepton ISO (\(\ell\ell\gamma\)), \(\gamma\)-ID, JES, lumi, \(\gamma\)-ISO (\(\nu\nu\gamma\))

\(6\sigma\) combined \(\ell\ell\gamma\gamma\) significance
Multiple gauge boson measurements: aGC

**Coupling combinations**

**Charged couplings:**
\( \gamma WW, ZWW, WWZZ, WWZ\gamma, WW\gamma\gamma \) - allowed within the SM.

**Neutral couplings:**
\( ZZ\gamma, \gamma\gamma Z, ZZZ, ZZ\gamma\gamma, Z\gamma\gamma\gamma \) - not allowed within the SM.

**Anomalous coupling approaches**

**aTGC:** effective Lagrangian

**aQGC:** effective field theory

**Parameters of the couplings:**

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Parameters</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW(\gamma)</td>
<td>(\lambda_{\gamma}, \Delta k_{\gamma})</td>
<td>WW, W(\gamma)</td>
</tr>
<tr>
<td>WWZ</td>
<td>(\lambda Z, \Delta k Z, 4g_{\gamma}^2)</td>
<td>WW, WZ</td>
</tr>
<tr>
<td>ZZ(\gamma)</td>
<td>(h^Z_3, h^Z_4)</td>
<td>Z(\gamma)</td>
</tr>
<tr>
<td>Z(\gamma)</td>
<td>(h^\gamma_3, h^\gamma_4)</td>
<td>Z(\gamma)</td>
</tr>
<tr>
<td>Z(\gamma)Z</td>
<td>(f_{\gamma 0}, f_{\gamma 5})</td>
<td>ZZ</td>
</tr>
<tr>
<td>Z(\gamma)Z</td>
<td>(f_{\gamma 0}, f_{\gamma 5})</td>
<td>ZZ</td>
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**Table of couplings**

<table>
<thead>
<tr>
<th></th>
<th>WWWWW</th>
<th>WWZZZ</th>
<th>ZZZZZ</th>
<th>WW(\gamma)Z</th>
<th>WW(\gamma)\gamma</th>
<th>ZZZ(\gamma)</th>
<th>ZZZ(\gamma\gamma)</th>
<th>ZZZ(\gamma\gamma\gamma)</th>
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<tbody>
<tr>
<td>(L_{S,0}, L_{S,1})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>(L_{M,0}, L_{M,1}, L_{M,6}, L_{M,7})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(L_{M,2}, L_{M,3}, L_{M,4}, L_{M,5})</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>(L_{T,0}, L_{T,1}, L_{T,2})</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(L_{T,5}, L_{T,6}, L_{T,7})</td>
<td>O</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>(L_{T,8}, L_{T,9})</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>X</td>
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E. Soldatov  |  ICNFP’16  |  09.07.2016  |  № 19
**Latest aTGC results: charged couplings**

### Effect of aTGC on kinematic distributions:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\mathcal{L} \text{ fb}^{-1}$</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>[-4.3e-02, 4.3e-02]</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-6.0e-02, 4.6e-02]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-8.6e-02, 4.8e-02]</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-1.9e-01, 3.0e-01]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-7.4e-02, 5.1e-02]</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-9.0e-02, 1.0e-01]</td>
<td>5.0 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-9.4e-02, 3.3e-02]</td>
<td>0.7 fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
</tbody>
</table>

### $\Delta k_z$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\mathcal{L} \text{ fb}^{-1}$</th>
<th>$\sqrt{s}$</th>
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<tbody>
<tr>
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<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-1.9e-01, 1.9e-02]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-4.8e-02, 4.8e-02]</td>
<td>4.9 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-2.4e-02, 2.4e-02]</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-4.6e-02, 4.7e-02]</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-1.6e-02, 1.6e-02]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-3.9e-02, 4.0e-02]</td>
<td>4.6 fb$^{-1}$</td>
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<tr>
<td>WZ</td>
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<td>7 TeV</td>
</tr>
<tr>
<td>WZ</td>
<td>[-5.9e-02, 1.7e-02]</td>
<td>0.7 fb$^{-1}$</td>
<td>0.20 TeV</td>
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### $\lambda_z$

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<thead>
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<tbody>
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<td>4.9 fb$^{-1}$</td>
<td>7 TeV</td>
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<tr>
<td>WW</td>
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<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
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<tr>
<td>WZ</td>
<td>[-1.9e-02, 2.9e-02]</td>
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<td>8 TeV</td>
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<tr>
<td>WZ</td>
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<tr>
<td>WZ</td>
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<td>0.7 fb$^{-1}$</td>
<td>0.20 TeV</td>
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### $\Delta g_z$

<table>
<thead>
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<th>$\sqrt{s}$</th>
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<tbody>
<tr>
<td>WW</td>
<td>[-3.4e-02, 8.4e-02]</td>
<td>8.6 fb$^{-1}$</td>
<td>1.96 TeV</td>
</tr>
</tbody>
</table>

**aTGC Limits @95% C.L.**
Latest aTGC results: charged couplings II

Mar 2016

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\int L dt$</th>
<th>$\sqrt{s}$</th>
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<tbody>
<tr>
<td>$W_γ$</td>
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<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
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<td>$W_T$</td>
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<td>7 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-1.2e-01, 1.7e-01]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-2.1e-01, 2.2e-01]</td>
<td>4.9 fb$^{-1}$</td>
<td>7 TeV</td>
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<tr>
<td>WW</td>
<td>[-1.3e-01, 9.5e-02]</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
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<tr>
<td>WW</td>
<td>[-1.1e-01, 1.4e-01]</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>WW</td>
<td>[-1.6e-01, 2.5e-01]</td>
<td>5.0 fb$^{-1}$</td>
<td>7 TeV</td>
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<tr>
<td>D0 Comb.</td>
<td>[-5.9e-02, 6.6e-02]</td>
<td>8.6 fb$^{-1}$</td>
<td>1.96 TeV</td>
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<tr>
<td>LEP Comb.</td>
<td>[-9.9e-02, 6.6e-02]</td>
<td>0.7 fb$^{-1}$</td>
<td>0.20 TeV</td>
</tr>
</tbody>
</table>

ATLAS

$\sqrt{s} = 8$ TeV, $20.3$ fb$^{-1}$

95% C.L. with no constraints
Latest aTGC results: neutral couplings

$Z\gamma$ @ 8 TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\int L dt$</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\gamma(\ell\nu,\gamma\gamma)$</td>
<td>[-1.5e-02, 1.6e-02]</td>
<td>4.6 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$Z\gamma(\ell\nu,\nu\gamma)$</td>
<td>[-9.5e-04, 9.9e-04]</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma(\ell\gamma,\nu\gamma)$</td>
<td>[-2.9e-03, 2.9e-03]</td>
<td>5.0 fb$^{-1}$</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$Z\gamma(\ell\gamma,\gamma\gamma)$</td>
<td>[-4.6e-03, 4.6e-03]</td>
<td>19.5 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma(\nu\nu,\gamma\gamma)$</td>
<td>[-1.1e-03, 9.0e-04]</td>
<td>19.6 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma(\nu\gamma,\gamma\gamma)$</td>
<td>[-2.2e-02, 2.0e-02]</td>
<td>5.1 fb$^{-1}$</td>
<td>1.96 Te$^3$</td>
</tr>
</tbody>
</table>

$Z\gamma$ @ 8 TeV, 20.3 fb$^{-1}$
Latest aQGC results

Effect of aQGC on kinematic distributions:

$\gamma\gamma \rightarrow WW \, @ \, 8 \, TeV$

$\gamma\gamma \rightarrow WW \, @ \, 8 \, TeV$
## Latest aQGC results II

### Channel Limits

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\mathcal{L}_{\text{det}}$ (fb$^{-1}$)</th>
<th>$\mathcal{L}_{\text{s}}$ (8 TeV)</th>
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</thead>
<tbody>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-3.8e+01, 3.8e+01]$</td>
<td>19.4</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma\gamma$</td>
<td>$[-1.6e+01, 1.9e+01]$</td>
<td>20.3</td>
<td>8 TeV</td>
</tr>
<tr>
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<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-2.5e+01, 2.4e+01]$</td>
<td>19.3</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$[-3.8e+00, 3.4e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$[-5.4e+00, 5.6e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$[-4.2e+00, 4.6e+00]$</td>
<td>19.4</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-4.6e+01, 4.7e+01]$</td>
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<td>8 TeV</td>
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<td>$Z\gamma$</td>
<td>$[-4.4e+00, 4.4e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
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<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$[-2.1e+00, 2.4e+00]$</td>
<td>19.4</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-9.9e+00, 9.0e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-1.1e+01, 1.2e+01]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$[-5.9e+00, 7.1e+00]$</td>
<td>19.4</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
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<td>20.3</td>
<td>8 TeV</td>
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<td>$W\gamma\gamma$</td>
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<td>$W\gamma\gamma$</td>
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<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma\gamma$</td>
<td>$[-7.3e+00, 7.7e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$[-1.8e+00, 1.8e+00]$</td>
<td>19.7</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma$</td>
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<td>$Z\gamma$</td>
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<td>8 TeV</td>
</tr>
</tbody>
</table>

### aQGC Limits @95% C.L. [TeV$^{-4}$]

![EWK WZ @ 8 TeV](image_url)

- **Obs. 95% C.L. $W^\pm Z^{ij}$**
- **Exp. 95% C.L. $W^\pm Z^{ij}$**
- **1 $\sigma$ expected**
- **2 $\sigma$ expected**

**K-matrix unitarization**

pp $\rightarrow W^\pm Z^{ij}$

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**E. Soldatov**  |  **ICNFP'16**  |  **09.07.2016**  |  **№ 24**
Conclusions

- A lot of new results from ATLAS experiment were shown.

- Latest single and multiboson measurements using run1 and run2 datasets are compatible with SM expectations (NLO/NNLO).

- Many differential cross-section distributions published.

- Ratios of the cross sections allow to probe proton structure.

- Z boson decay angular coefficients allow to probe its production dynamics.

- Very strong aTGC and aQGC limits set. No deviations from SM observed.

- Looking forward to the new run2 results!
Motivation: Testing different aspects of QCD:
- soft gluon resummation
- fixed-order perturbative QCD predictions
- parton shower models

Selection for fiducial region:
$Z \rightarrow ee/\mu\mu$  $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$
\[ p_T(l) > 20 \text{ GeV} \quad |\eta_l|<2.4 \]

Result:
QCD predictions comparison with RESBOS
- Low $\phi^*_\eta$ and $d\sigma/dp_T^{||}$: dominated by soft-gluon-resummation effects → RESBOS predictions consistent with the data
- High $\phi^*_\eta$ and $d\sigma/dp_T^{||}$: sensitive to hard parton emissions → RESBOS differs from data

Comparison to PS approach and to fixed order QCD done also. Theoretical predictions describe data well.

Study $d\sigma/dp_T^{||}$ and $d\sigma/d\phi^*_\eta$ in bins of $m_{ll}$ and $|y_{ll}|$
Drell-Yan lepton pairs transverse momentum and $\phi^* @ 8$ TeV


**Comparison to PS approach:**

- For $5 < p_T(ll) < 100$ GeV description of MC is compatible with data at 10% level
- Powheg-Pythia – better agreement with data.
- Same study was performed for $d\sigma/d\phi^*_{\eta}$, which shows same behavior
- PS MC’s describe well (maximal discrepancies – 5%)
Drell-Yan lepton pairs transverse momentum and $\phi^*$ @ 8 TeV

*Comparison to fixed-order QCD:*

- Low $p_T^{ll}$ discrepancies expected because soft gluon emissions dominant
- Good shape description for $p_T^{ll} > 30$ GeV, but normalization systematically 15% lower than data
- Recent NNLO calculations show improved agreement with data
Limits on Anomalous Gauge Couplings: $Z\gamma/Z\gamma\gamma$

**aTGC**

**Vertex function approach**

**ATLAS Preliminary** 95% C.L., $\Lambda = \infty$

$\times 10^3$ Coupling strength

- $W^+W^-$ CMS, $\sqrt{s}=8$ TeV, 19.4 fb$^{-1}$
- $W\gamma\gamma$ ATLAS, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$
- $Z\gamma\gamma$ ATLAS, $\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$
- $WW\gamma$ CMS, $\sqrt{s}=8$ TeV, 19.3 fb$^{-1}$

**aQGC**

**EFT approach**

**ATLAS Preliminary** 95% C.L.

$\Lambda_{\text{FF}} = \infty$

Coupling strength [TeV$^{-4}$]

- $f_{10}/\Lambda^4$
- $f_{15}/\Lambda^4$
- $f_{19}/\Lambda^4$

No sign of deviation from SM predictions

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