Electroweak Results from ATLAS

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On behalf of the ATLAS Collaboration

<https://twiki.cern.ch/twiki/bin/view//AtlasPublic>

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σ [pb]

EW Physics in ATLAS

10^4

Single W, Z production

A_{FB} in $Z \rightarrow \ell\ell$

precision EW

$\sin^2\theta_W$, (m_W)

1–50

Diboson production

$WW, WZ, ZZ, W\gamma, Z\gamma$

$Z \rightarrow 4\ell$ ($ZZ^*/Z\gamma^*$)

TGC's

10^{-1}

Vector boson fusion (VBF)

Zjj

EWSB

10^{-2}

Vector boson scattering (VBS)

$WWjj$

QGC's

10^{-3}

σ [pb]

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10^{-1}

10^{-2}

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Zjj

10^{-3}

Vector boson scattering (VBS)

$WWjj$

PLAN

TGC's

EWSB

QGC's

$W^\pm W^\pm jj$: VBS

Sensitive to quartic gauge couplings (QGCs)

$W_L W_L \rightarrow W_L W_L$ violates unitarity without a SM Higgs

→ *two high momentum, forward jets*

plus non-VBS EW :

$W^\pm W^\pm jj$: EW and QCD

plus strong (QCD) contributions :

To extract $WWjj$ -EW :

use $W^\pm W^\pm$: -- smaller VBS cross section than W^+W^-
(same-charge) but (much) lower $WWjj$ -QCD contribution

use $|\Delta y(jj)|$, $m(jj)$:

-- tend to be larger for $WWjj$ -EW than for $WWjj$ -QCD

$W^\pm W^\pm jj$: event selection

Further background rejection :

- lepton veto: $p_T(e, \mu) > 7,6 \text{ GeV}$ (reduce WZ/ZZ)
- Z veto: $|m(e^\pm e^\pm) - m_Z| > 10 \text{ GeV}$ (reduce DY)
- b-jet veto (reduce $t\bar{t}$)

$W^\pm W^\pm jj$: jet-jet mass

WWjj signal MC :

SHERPA (LO, up to 3 jets)

normalised to
POWHEG (NLO QCD)

cross-checked with
VBFNLO

$m(jj) > 500$ GeV

→ **50** events

(background ≈ 20 evts)

$e^\pm \mu^\pm$: **26** evts

$e^\pm e^\pm$: **12** evts

$\mu^\pm \mu^\pm$: **12** evts

$W^\pm W^\pm jj$: fiducial cross section

WWjj-EW + WWjj-QCD + interference

$$\sigma_{\text{fid}} = \frac{N_{\text{obs.}} - N_{\text{bgd.}}}{\mathcal{L} \times \varepsilon}$$

56–83%

$$\sigma_{\text{WWjj-SM}} = 1.52 \pm 0.11 \text{ fb}$$

$$\left[\begin{array}{ll} \text{WWjj-EW} & : \quad 1.00 \pm 0.06 \text{ fb} \\ \text{WWjj-QCD} & : \quad 0.35 \pm 0.05 \text{ fb} \\ & + \text{ interference} \end{array} \right]$$

$$\sigma_{\text{fid}} = 2.1 \pm 0.5 \pm 0.3 \text{ fb}$$

ATLAS

20.3 fb⁻¹, $\sqrt{s}=8 \text{ TeV}$

SM $\sigma_{\text{WW}}^{\text{incl}} = 1.52 \pm 0.11 \text{ [fb]}$
NLO, POWHEG-BOX, CT10

$e^\pm e^\pm$

$2.0 \pm 1.5 \pm 0.5 \text{ [fb]}$

$e^\pm \mu^\pm$

$2.1 \pm 0.7 \pm 0.3 \text{ [fb]}$

$\mu^\pm \mu^\pm$

$2.2 \pm 0.9 \pm 0.2 \text{ [fb]}$

Combination

$2.1 \pm 0.5 \pm 0.3 \text{ [fb]}$

$\sigma_{\text{WW}}^{\text{incl.}} \text{ [fb]}$

Background-only hypothesis excluded at **4.5 σ** (exp 3.4 σ)

$W^\pm W^\pm jj$: extract EW component

Use “VBS” region : $|\Delta y_{jj}| > 2.4$

WWjj-EW + interference

Background-only hypothesis excluded at 3.6σ (exp 2.8σ)

→ **first evidence for EW $W^\pm W^\pm jj$ production**

$W^\pm W^\pm jj$: QGC limits

Use measured “VBS” cross section to limit aQGCs :

Use **WHIZARD+PYTHIA8**
with K-matrix unitarisation

→ first limits on α_4, α_5

(95% CL)	α_4	α_5
Measured	$[-0.14, +0.16]$	$[-0.23, +0.24]$
Expected	$[-0.10, +0.12]$	$[-0.18, +0.20]$

Zjj : VBF

EW Zjj production :

Sensitive to anomalous WWZ triple gauge couplings (aTGCs)

Similar to VBF production of a Higgs boson :

Zjj : EW and QCD

Plus :

Zjj-QCD (dominant)

diboson (small)

Separating Zjj-EW from Zjj-QCD :

$|\Delta y(jj)|$, $m(jj)$, $p_T(j)$ -- tend to be larger for Zjj-EW

$N(\text{jet, gap})$ -- fewer additional jets for Zjj-EW

(colourless exchange region) $\longrightarrow$

Zjj : event selection

Fid region	$N(\text{jet, gap})$	$m(jj)$	Zjj-QCD	Zjj-EW	WZ,ZZ	Top
"search"	= 0	> 250 GeV	94.7%	4.0%	0.7%	0.6%
"high mass"	≥ 0	> 1 TeV	85%	12%	1%	2%

... plus "baseline", "control" and "high- p_T " regions
 (to check inclusive Zjj and Zjj-QCD modelling)

Zjj : jet-jet mass and Δy

“baseline” region : no cuts on $m(jj)$ or $N(\text{jet,gap})$

- Zjj signal : SHERPA (LO) normalised to POWHEG (NLO QCD)
- top bgd : MC@NLO+HERWIG/JIMMY, normalised to NNLO QCD
- multijet bgd : from data (reverse some e, μ id cuts)

Zjj : N(jet, gap)

“high mass” region

[$m(jj) > 1000 \text{ GeV}$]

unfolded distribution
(one of many)

fewer additional jets
for Zjj-EW component

Zjj : fiducial cross sections

(Zjj-EW ~ 4%)

“search” region :

$$\sigma_{\text{fid}} = 1.10 \pm 0.01 \pm 0.09 \pm 0.03(\text{lumi}) \text{ pb}$$

$$\sigma_{\text{theory}} = 1.23 \pm 0.01(\text{stat})_{-0.13}^{+0.11}(\text{scale})_{-0.07}^{+0.06}(\text{PDF})_{-0.04}^{+0.03}(\text{model}) \text{ pb}$$

(POWHEG)

(Zjj-EW ~ 12%)

“high mass” region :

$$\sigma_{\text{fid}} = 66 \pm 1 \pm 12 \pm 2(\text{lumi}) \text{ fb}$$

$$\sigma_{\text{theory}} = 68 \pm 1(\text{stat})_{-9}^{+9}(\text{scale})_{-3}^{+4}(\text{PDF})_{-2}^{+4}(\text{model}) \text{ fb}$$

To extract Zjj-EW : fit m(jj) distribution in “search” region

- *signal template* : SHERPA Zjj-EW
- *bgd template* : SHERPA Zjj-QCD

(plus small diboson, top contributions)

→ constrained using data “control” region

Zjj : extract EW component

“control” region

“search” region

Zjj-EW : fiducial cross sections

Results of fit to $m(jj)$ distribution :

(Zjj-EW ~ 4%)

$$\sigma_{\text{fid}}(\text{Zjj} - \text{EW}) = 54.7 \pm 4.6(\text{stat})_{-10.4}^{+9.8}(\text{syst}) \pm 1.5(\text{lumi}) \text{ fb}$$

$$\sigma_{\text{SM}} = 46.1 \pm 0.2(\text{stat})_{-0.2}^{+0.3}(\text{scale}) \pm 0.8(\text{PDF}) \pm 0.5(\text{model}) \text{ fb}$$

For “search” region with $m(jj) > 1 \text{ TeV}$:

(Zjj-EW ~ 35%)

$$\sigma_{\text{fid}}(\text{Zjj} - \text{EW}) = 10.7 \pm 0.9(\text{stat}) \pm 1.9(\text{syst}) \pm 0.3(\text{lumi}) \text{ fb}$$

$$\sigma_{\text{SM}} = 9.38 \pm 0.05(\text{stat})_{-0.24}^{+0.15}(\text{scale}) \pm 0.24(\text{PDF}) \pm 0.09(\text{model}) \text{ fb}$$

Background-only hypothesis excluded at over 5σ

(based on 10^9 pseudo-experiments)

Zjj : TGC limits

(WWZ vertex)

- use “search” region with $m(jj) > 1 \text{ TeV}$
(data = 900 evts, Zjj-EW(SM) ≈ 260 evts)

- restore unitarity with form factor :

$$a(\hat{s}) = \frac{a_0}{(1 + \hat{s}/\Lambda^2)^2}$$

95% CL allowed regions : ($\Lambda = \infty$: no form factor, violates unitarity)

	$\Delta g_{1,Z}$		λ_Z	
	$\Lambda = 6 \text{ TeV}$	$\Lambda = \infty$	$\Lambda = 6 \text{ TeV}$	$\Lambda = \infty$
Obs.	$[-0.65, +0.33]$	$[-0.50, +0.26]$	$[-0.22, +0.19]$	$[-0.15, +0.13]$
Exp.	$[-0.58, +0.27]$	$[-0.45, +0.22]$	$[-0.19, +0.16]$	$[-0.14, +0.11]$

- not as stringent as limits from WZ production (see later)

but *complementary* : the two W's are *space-like*

Dibosons : W^+W^-

$q\bar{q} \rightarrow W^+W^-$ (dominant)

$gg \rightarrow W^+W^-$ ($\approx 9\%$)

$E_T(\text{miss}) > 45 \text{ (15) GeV}$
 $p_T(\text{miss}) > 45 \text{ (20) GeV}$
 $\Delta\phi(E_T, p_T)(\text{miss}) < 0.3 \text{ (0.6)}$

} $() = e^\pm \mu^\mp$
(looser)

- lepton veto: $p_T(e, \mu) > 7 \text{ GeV}$
- Z veto: $|m(l\bar{l}) - m_Z| > 15 \text{ GeV}$
- jet veto: $p_T(j) > 25 \text{ GeV}$

W^+W^- : jet multiplicity

Before jet-veto requirement :

(bgds from MC)

(select)

(select)

→ **6636** W^+W^- candidates

5067 ($e\mu$) + 594 (ee) + 975 ($\mu\mu$)

($\approx 8\%$ from $W \rightarrow \tau$)

W^+W^- : selected events

dilepton mass $m(\ell\ell)$

- WW scaled ($\times 1.21$) to match measured cross section (POWHEG + GG2WW)
- backgrounds : data-driven for top, W+jets, Z+jets

W^+W^- : total cross section

$$\sigma_{\text{SM}} = 58.7^{+3.0}_{-2.7} \text{ pb}$$

$$\sigma_{WW} = 71.4 \pm 1.2(\text{stat})^{+5.0}_{-4.4}(\text{syst})^{+2.2}_{-2.1}(\text{lumi}) \text{ pb}$$

$\approx 20\% (2.1\sigma)$ higher than SM expectation

$$\left[\begin{array}{ll} qq \rightarrow WW : & 53.2 \text{ pb} \\ gg \rightarrow WW : & 1.4 \text{ pb} \\ gg \rightarrow H \rightarrow WW : & 4.1 \text{ pb} \end{array} \right]$$

$$\left[\begin{array}{ll} -- \text{ k-factor for } gg \rightarrow WW ? & -- \text{ NNLO corrections ?} \\ -- \text{ PDF variations ?} & -- \text{ EW NLO corrections ?} \end{array} \right]$$

Diboson Cross Section Measurements

Status: July 2014

$\int \mathcal{L} dt$
[fb⁻¹]

Reference

$\sigma^{\text{fid}}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$

$\sigma = 44.0 \pm 0.0 + 3.2 - 4.2 \text{ pb (data)}$
 $2\gamma\text{NNLO (theory)}$

4.9

JHEP 01, 086 (2013)

$\sigma^{\text{fid}}(W\gamma \rightarrow \ell\nu\gamma)$

$\sigma = 2.77 \pm 0.03 \pm 0.36 \text{ pb (data)}$
MCFM (theory)

4.6

PRD 87, 112003 (2013)

– [n_{jet} = 0]

$\sigma = 1.76 \pm 0.03 \pm 0.22 \text{ pb (data)}$
MCFM (theory)

4.6

PRD 87, 112003 (2013)

$\sigma^{\text{fid}}(Z\gamma \rightarrow \ell\ell\gamma)$

$\sigma = 1.31 \pm 0.02 \pm 0.12 \text{ pb (data)}$
MCFM (theory)

4.6

PRD 87, 112003 (2013)

– [n_{jet} = 0]

$\sigma = 1.05 \pm 0.02 \pm 0.11 \text{ pb (data)}$
MCFM (theory)

4.6

PRD 87, 112003 (2013)

$\sigma^{\text{total}}(\text{pp} \rightarrow \text{WW} + \text{WZ})$

$\sigma = 72.0 \pm 9.0 \pm 19.8 \text{ pb (data)}$
MCFM (theory)

4.7

ATLAS-CONF-2012-157

$\sigma^{\text{fid}}(W^\pm W^\pm jj) \text{ EWK}$

$\sigma = 1.3 \pm 0.4 \pm 0.2 \text{ fb (data)}$
PowhegBox (theory)

20.3

arXiv:1405.6241 [hep-ex]

$\sigma^{\text{total}}(\text{pp} \rightarrow \text{WW})$

$\sigma = 51.9 \pm 2.0 \pm 4.4 \text{ pb (data)}$
MCFM (theory)
 $\sigma = 71.4 \pm 1.2 \pm 5.5 - 4.9 \text{ pb (data)}$
MCFM (theory)

4.6

PRD 87, 112001 (2013)

– $\sigma^{\text{fid}}(\text{WW} \rightarrow e\bar{e})$

$\sigma = 56.4 \pm 6.8 \pm 10.0 \text{ fb (data)}$
MCFM (theory)

4.6

PRD 87, 112001 (2013)

– $\sigma^{\text{fid}}(\text{WW} \rightarrow \mu\mu)$

$\sigma = 73.9 \pm 5.9 \pm 7.5 \text{ fb (data)}$
MCFM (theory)

4.6

PRD 87, 112001 (2013)

– $\sigma^{\text{fid}}(\text{WW} \rightarrow e\mu)$

$\sigma = 262.3 \pm 12.3 \pm 23.1 \text{ fb (data)}$
MCFM (theory)

4.6

PRD 87, 112001 (2013)

$\sigma^{\text{total}}(\text{pp} \rightarrow \text{WZ})$

$\sigma = 19.0 \pm 1.4 - 1.3 \pm 1.0 \text{ pb (data)}$
MCFM (theory)
 $\sigma = 20.3 \pm 0.8 - 0.7 \pm 1.4 - 1.3 \text{ pb (data)}$
MCFM (theory)

4.6

EPJC 72, 2173 (2012)

– $\sigma^{\text{fid}}(\text{WZ} \rightarrow \ell\nu\ell\ell)$

$\sigma = 99.2 \pm 3.8 - 3.0 \pm 6.0 - 6.2 \text{ fb (data)}$
MCFM (theory)

13.0

ATLAS-CONF-2013-021

$\sigma^{\text{total}}(\text{pp} \rightarrow \text{ZZ})$

$\sigma = 6.7 \pm 0.7 \pm 0.5 - 0.4 \text{ pb (data)}$
MCFM (theory)
 $\sigma = 7.1 \pm 0.5 - 0.4 \pm 0.4 \text{ pb (data)}$
MCFM (theory)

4.6

JHEP 03, 128 (2013)

– $\sigma^{\text{total}}(\text{pp} \rightarrow \text{ZZ} \rightarrow 4\ell)$

$\sigma = 76.0 \pm 18.0 \pm 4.0 \text{ fb (data)}$
Powheg (theory)
 $\sigma = 107.0 \pm 9.0 \pm 5.0 \text{ fb (data)}$
Powheg (theory)

20.3

arXiv:1403.5657 [hep-ex]

– $\sigma^{\text{fid}}(\text{ZZ} \rightarrow 4\ell)$

$\sigma = 25.4 \pm 3.3 - 3.0 \pm 1.6 - 1.4 \text{ fb (data)}$
PowhegBox & gg2ZZ (theory)
 $\sigma = 20.7 \pm 1.3 - 1.2 \pm 1.0 \text{ fb (data)}$
MCFM (theory)

4.6

JHEP 03, 128 (2013)

– $\sigma^{\text{fid}}(\text{ZZ}^* \rightarrow 4\ell)$

$\sigma = 29.8 \pm 3.8 - 3.5 \pm 2.1 - 1.9 \text{ fb (data)}$
PowhegBox & gg2ZZ (theory)

4.6

JHEP 03, 128 (2013)

– $\sigma^{\text{fid}}(\text{ZZ}^* \rightarrow \ell\ell\nu\nu)$

$\sigma = 12.7 \pm 3.1 - 2.9 \pm 1.8 \text{ fb (data)}$
PowhegBox & gg2ZZ (theory)

4.6

JHEP 03, 128 (2013)

ATLAS Preliminary
Run 1 $\sqrt{s} = 7, 8 \text{ TeV}$

LHC pp $\sqrt{s} = 7 \text{ TeV}$

Theory
Data
stat
stat+syst

LHC pp $\sqrt{s} = 8 \text{ TeV}$

Theory
Data
stat
stat+syst

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

data/theory

pp $\rightarrow$ 4l

From Higgs analysis :

$Z \rightarrow 4l$

Go to lower l^+l^- mass :

Also $gg \rightarrow ZZ$:

($\sim 10^{-3}$ near Z mass)

$Z \rightarrow 4l$: event selection

Use $H \rightarrow 4l$ selection, with looser cuts

- $m(l\bar{l}) > 5 \text{ GeV}$
(for all e^+e^- and $\mu^+\mu^-$ pairs)
- $m_{12} > 20 \text{ GeV}$
- $p_T(e, \mu) > 20, 15, 10(8), 7(4) \text{ GeV}$

Require $80 < m(4l) < 100 \text{ GeV} \rightarrow$ **172** selected events :

	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$4l$
7 TeV	1	8	12	21
8 TeV	16	71	64	151

4e, 4 μ pairing ambiguity : “12” = highest mass l^+l^- pair

$Z \rightarrow 4l$: selected events

All channels combined

background = 1.4 ± 0.2 events ($< 1\%$)

BR(Z → 4l)

PRL **112** (2014) 231806

[[arXiv:1403.5657](https://arxiv.org/abs/1403.5657)]

s-channel only : subtract non-resonant contributions

	4e, 4μ	2e2μ
f_t	$(3.35 \pm 0.02) \%$	$(3.90 \pm 0.02) \%$

(POWHEG, NLO QCD)

[interference with s-channel small ($\sim 0.2\%$, included in systematic error)
 interference between identical leptons in final state : $4e, 4\mu \neq 2e2\mu$]

Normalise to $Z \rightarrow \mu^+ \mu^-$ data : ($\sim 10^7$ events)

→ cancels luminosity and (some) theory uncertainties

$$\text{BR}(Z \rightarrow 4\ell) = \text{BR}(Z \rightarrow \mu^+ \mu^-) (1 - f_t - f_{gg}) \frac{(N_{\text{obs}}^{4\ell} - N_{\text{bgd}}^{4\ell}) \varepsilon^{2\mu}}{(N_{\text{obs}}^{2\mu} - N_{\text{bgd}}^{2\mu}) \varepsilon^{4\ell}}$$

(3.366 ± 0.007)% (PDG)

Measured BR(Z → 4l)

$$(3.20 \pm 0.25 \pm 0.13) \times 10^{-6}$$

Predicted

$$(3.33 \pm 0.01) \times 10^{-6}$$

$m(l\bar{l}) > 5 \text{ GeV}$

$80 < m(4l) < 100 \text{ GeV}$

Dibosons : anomalous TGC's

NEUTRAL

CHARGED

ZZ

Z γ

WW, W γ , WZ

$$f_4^{\gamma,Z}, f_5^{\gamma,Z}$$

$$h_3^{\gamma,Z}, h_4^{\gamma,Z}$$

$$\lambda_{\gamma,Z}, \Delta\kappa_Z, \Delta g_1^Z$$

SM : forbidden at tree-level
 $(f_4^{\gamma,Z} = f_5^{\gamma,Z} = h_3^{\gamma,Z} = h_4^{\gamma,Z} = 0)$

SM : $\lambda_\gamma = \lambda_Z = 0$
 $\kappa_\gamma = \kappa_Z = g_1^Z = 1$

- signature : cross sections (much) enhanced at high p_T
- problem : unitarity violation at high energy

Neutral TGC's : ZZ

$ZZ \rightarrow 4l$

$ZZ \rightarrow ll\nu\nu$

Limits factor 5-10 better than LEP, Tevatron (even for 7 TeV data alone) :

Λ	f_4^γ	f_4^Z	f_5^γ	f_5^Z
3 TeV	$[-0.022, +0.023]$	$[-0.019, +0.019]$	$[-0.023, +0.023]$	$[-0.020, +0.019]$
∞	$[-0.015, +0.015]$	$[-0.013, +0.013]$	$[-0.016, +0.015]$	$[-0.013, +0.013]$

Neutral TGC's : $Z\gamma$

“exclusive” :
 $N(\text{jet}) = 0$
 $E_T(\text{jet}) > 30 \text{ GeV}$

Limits factor 2-10 better than LEP (even for 7 TeV data alone) :

Λ	h_3^γ	h_3^Z	$h_4^\gamma / 10^{-4}$	$h_4^Z / 10^{-4}$
3 TeV	$[-0.023, +0.024]$	$[-0.018, +0.020]$	$[-3.7, +3.6]$	$[-3.1, +3.1]$
∞	$[-0.015, +0.016]$	$[-0.013, +0.014]$	$[-0.94, +0.92]$	$[-0.87, +0.87]$

Charged TGC's : WW , WZ , $W\gamma$

Vary one parameter at a time; no form factor ($\Lambda = \infty$)

Parameter	WW	WZ	$W\gamma$
$\Delta\kappa_\gamma$	$[-0.135, +0.190]$		$[-0.41, +0.46]$
λ_γ	$[-0.152, +0.146]$		$[-0.065, +0.061]$
$\Delta\kappa_Z$	$[-0.078, +0.092]$	$[-0.37, +0.57]$	
λ_Z	$[-0.074, +0.073]$	$[-0.046, +0.047]$	
Δg_1^Z	$[-0.373, +0.562]$	$[-0.057, +0.093]$	

... plus (tighter) limits in “LEP”, “HISZ” and “equal couplings” scenarios

- approaching combined sensitivity of LEP experiments
- 8 TeV results still to come

Summary

Dibosons :

- measured cross sections agree with SM
(but W^+W^- a bit high?)
- TGC limits : charged $\sim$ LEP, neutral $\sim$ LEP/(5-10)
(8 TeV results still to come)
- $Z \rightarrow 4l$ rare decay measured to $\pm 10\%$

VBS / VBF program now underway :

- EW Zjj production observed
- evidence for EW $W^\pm W^\pm jj$ production