Recent Electroweak Results from ATLAS

QCD@LHC 14

James Henderson
on behalf of the ATLAS collaboration

Oxford University, UK

27^{th} August 2014

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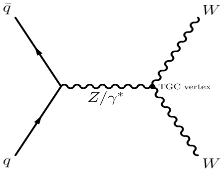
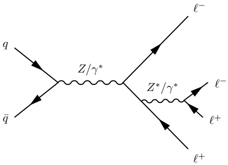
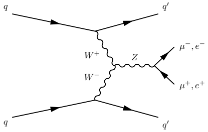
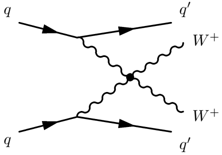
Introduction





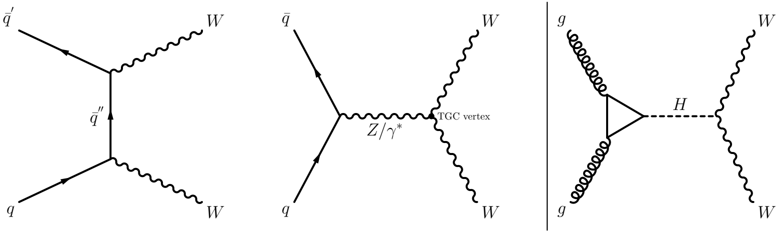




- Progress in small cross section SM discovery and precision physics
- SM standard candles used for path-finders to beyond the SM physics searches
- Precision measurements of anomalous triple/quartic gauge couplings
- Test of electroweak symmetry breaking in action

- Related Talks:
  - *Vector boson production and associated vector boson production with heavy flavors in ATLAS*
    Mikhail Levtchenko, Tuesday 09:30
  - *ATLAS measurements of vector boson production with associated jets*
    Craig Sawyer, Wednesday 09:50

- Test of SM diboson W^+W^- total cross section
- Background to $H \rightarrow W^+W^-$ analysis

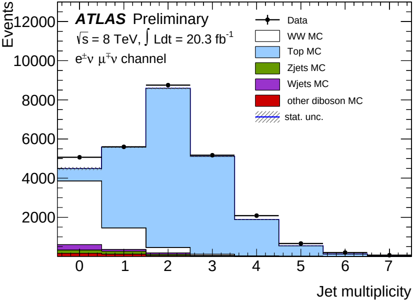


$q\bar{q} \rightarrow W^+W^-$ $gg \rightarrow W^+W^-$

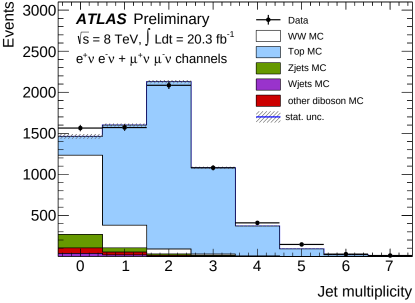
- $q\bar{q} \rightarrow W^+W^-$ expected to dominate 91% of cross-section (NLO)
- 3 separate lepton channels: $e^{\pm}e^{\mp}$,$\mu^{\pm}\mu^{\mp}$ and $e^{\pm}\mu^{\mp}$
- $e^{\pm}\mu^{\mp}$ has looser cuts due to fewer Z backgrounds

Event Selection

- Selection [$e^{\pm}\mu^{\mp}$ specific, ($e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$ specific)]:
  - Lepton $p_T > 25(20)$ GeV
  - No 3rd lepton $p_T > 7$ GeV
  - $E_T^{miss} > 15(45)$ GeV
  - $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss}\right) < 0.6(0.3)$
  - Veto jets $p_T > 25$ GeV
  - $m_{ll} > 10(15)$ GeV
  - $p_T^{miss} > 20(45)$ GeV
  - $|m_{ll} - m_Z| > 15$ GeV

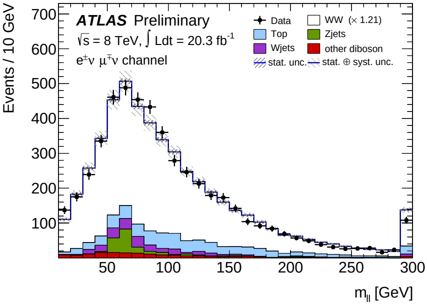


$e^{\pm}\mu^{\mp}$

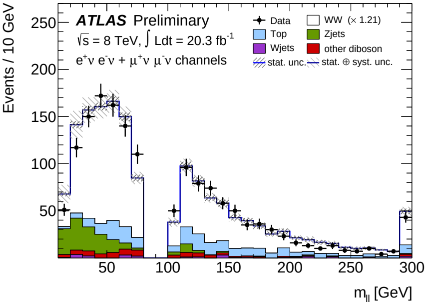


$e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$

- Signal extraction leads to W^+W^- scale factor 1.21
- Signal MC is POWHEG and *GG2WW*
- Data driven backgrounds: Drell-Yan, Top and W+Jets/Multijets



$e^{\pm}\mu^{\mp}$

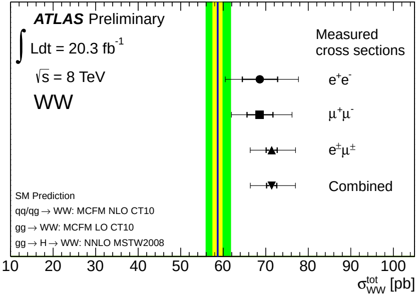


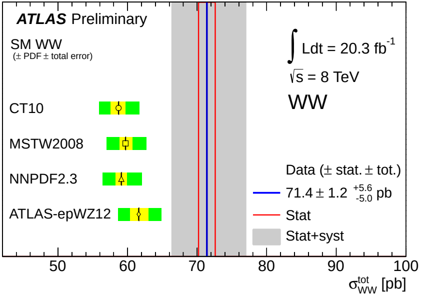
$e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$

- Observed events:
  - 5067 ($e^{\pm}\mu^{\mp}$) events
  - 594 ($e^{\pm}e^{\mp}$) & 975 ($\mu^{\pm}\mu^{\mp}$) events

Total Cross Section Results

- Theory prediction: $58.7^{+3.0}_{-2.7}$ pb
- Measured: $71.4^{+1.2}_{-1.2}$ (stat.) $^{+5.0}_{-4.4}$ (syst.) $^{+2.2}_{-2.0}$ (lumi.) pb





- $\sigma^{total}_{WW} =\sim 1.2 \times \sigma^{total}_{SM,WW}$ (2.1σ high)
- Possible explanation:
  - NNLO cross section predictions
  - Jet Veto efficiency modelling

Yellow bands: 68% limit

Green bands: 95% limit

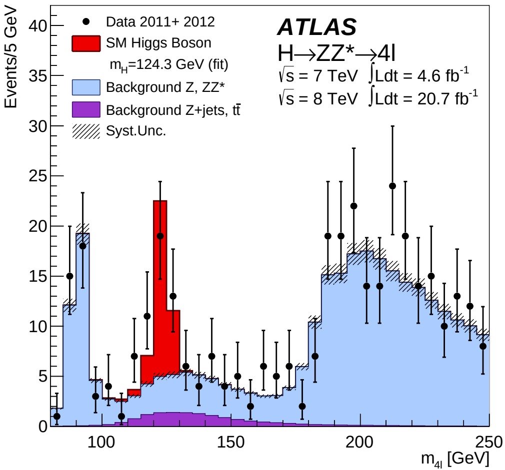
$Z \to 4l$ Higgs similarities

PLB 726(2013)88

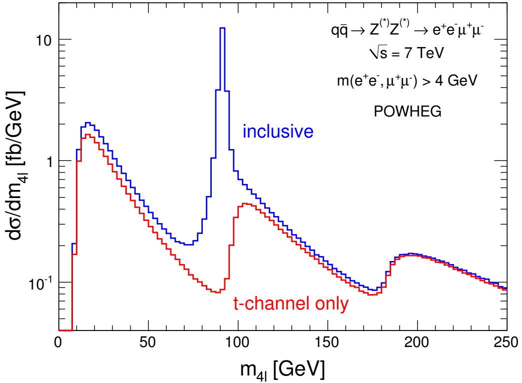
- Higgs to 4 leptons analysis observes large Z resonance

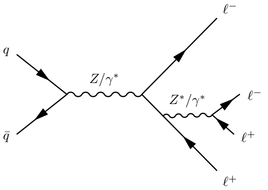
- Higgs $\to$ 4l:
- $m_{12(34)}$: invariant mass of leading(sub-leading) lepton pair
- $50 < m_{12} < 106$ GeV
- $12(50) < m_{34} < 115$ GeV for $m_{4l} < 140$ (190)

- $Z \to 4l$ standard candle in calibration of 4l analyses

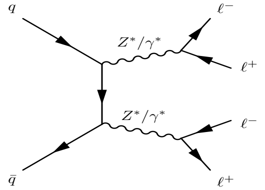


- $Z \rightarrow 4l$ analysis aims, measure:
  - Production cross-section of $Z \rightarrow 4l$
  - Branching fraction of $Z \rightarrow 4l$
- Focused on lower mass window than Higgs
- $80 < m_{4l} < 100$ GeV
- Generator level plot:





"resonant" s-channel



"non-resonant" t-channel

$gg \rightarrow 4l$ component $< 0.1\%$

t-chan. & $gg \rightarrow 4l \sim 4\%$ contribution

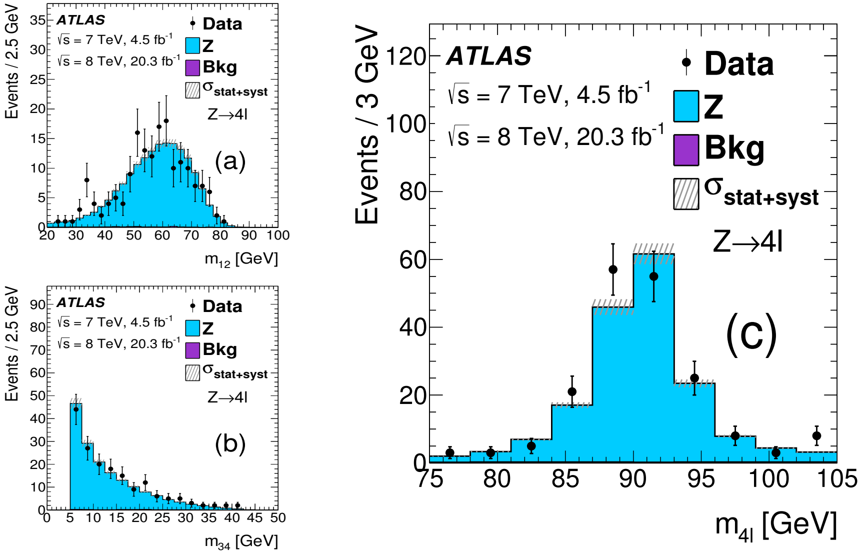
- Lower m_{4l}, looser cuts version of $H \rightarrow 4l$
- Selection (m_{XY} : **S**ame **F**lavour **O**pposite **S**ign (SFOS) lepton pair):
  - $|\eta| < 2.5(2.7)$ for e (μ)
  - $p_T > 20, 15, 10(8), 7(4)$ for e (μ)
  - $m_{12} > 20$ GeV, $m_{34} > 5$ GeV
  - $80 < m_{4l} < 100$ GeV
- $< 1\%$ backgrounds expected from:
  - Z+Jets and $t\bar{t}$: estimated with data-driven method
  - WZ, $gg \rightarrow ZZ$ and τ decays from Z: MC estimation

	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\mu^+\mu^-e^+e^-$	Total
7 TeV	1	8	7	5	21
8 TeV	16	71	48	16	151

Table: Event yields for 7 and 8 TeV

- 4e, 4μ ambiguity: m_{12} highest mass l^+l^- SFOS pair

$Z \to 4l$ Mass Plots



$Z \rightarrow 4l$ Cross Section Results

	NLO Predicted Cross Section (fb)	Measured Cross Section (fb)
7 TeV	132.0 ± 3.0	114 ± 27(stat.) ± 7(syst.) ± 2(lumi.)
8 TeV	153.8 ± 3.7	150 ± 13(stat.) ± 7(syst.) ± 5(lumi.)

- Statistical uncertainty dominant
- Main systematic components:
    - Lepton identification and reconstruction efficiencies ($\sim 10\%$ in 4e channel)
    - Theory uncertainties (α_s, PDF & scales): $\sim 1.5\%$
    - Luminosity: 1.8% for 7 TeV and 3.6% for 8 TeV

- Measurements in good agreement with SM prediction

$Z \rightarrow 4l$ Branching Ratio Results

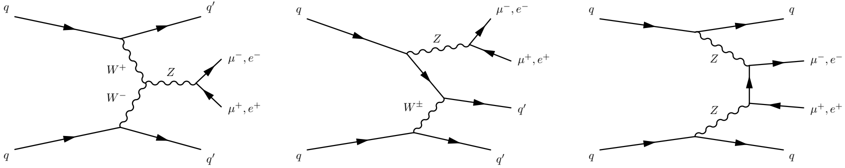
- Branching Ratio calculated for **s-channel only**
- Fraction of non-resonant contributions (f_{nr}) subtracted
- Interference in identical final state leptons means $\sigma_{4e,4\mu} \neq \sigma_{2e2\mu}$

	$4e, 4\mu$	$2e2\mu$
f_{nr}	$(3.45 \pm 0.02)\%$	$(4.00 \pm 0.02)\%$

- Normalised to high stats (10^7 *events*) $Z \rightarrow \mu\mu$ data
- Cancel lumi. and some theory errors

$$BR(Z \rightarrow 4l) = BR(Z \rightarrow \mu^+\mu^-)(1 - f_{nr}) \frac{(N^{4l}_{obs} - N^{4l}_{bkg})}{(N^{2\mu}_{obs} - N^{2\mu}_{bkg})} \frac{\varepsilon^{2\mu}}{\varepsilon^{4l}}$$

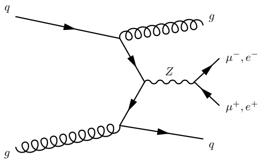
Predicted BR($Z \rightarrow 4l$)	Measured BR($Z \rightarrow 4l$)
$(3.33 \pm 0.01) \times 10^{-6}$	$(3.20 \pm 0.25 \pm 0.13)\ ^{-6}$



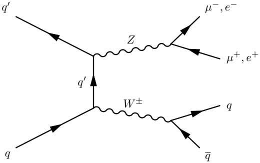
VBF Z-Bremsstrahlung Non-resonant

- First observation of small σ SM process
- Access to anomalous WWZ triple gauge couplings
- Similar kinematics and scale to VBF Higgs production

- Analysis aims:
  - Measurements of inclusive (QCD & Electroweak (EWK)) Z_{jj} production in five fiducial regions
  - Observation and measurement of fiducial cross section of *Electroweak Zjj* and place limits on aTGCs



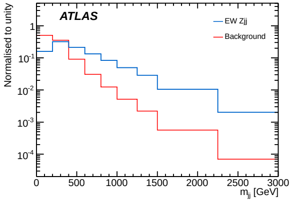
QCD Z_{jj}

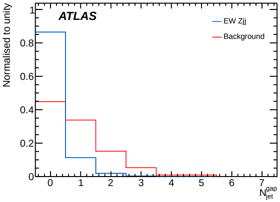


Diboson

- Dominant background from QCD Z_{jj}
- Interference between QCD Z_{jj} and *Electroweak Zjj* expected to be minimal

- Background: QCD + Diboson + ...
- *Electroweak Zjj* has high mass, large separation tagging jets
- Purely EWK process → less hadronic activity

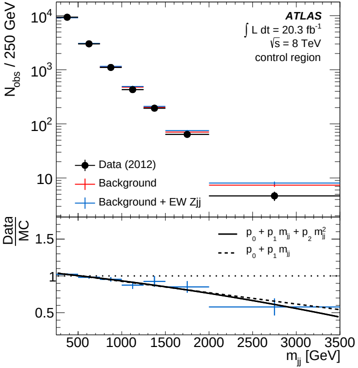




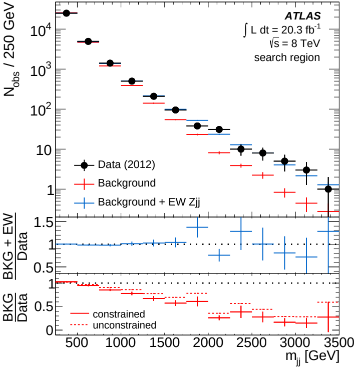
Electroweak Zjj Signal Extraction

- Veto 3rd jet ($p_T > 25$ GeV) in jet η gap (Reversed in Control Region)
- Z-boson from isolated lepton (e,μ)
- $81 < m_{ll} < 101$ GeV, $p_T^{ll} > 20$ GeV
- $p_T^{j1} > 55$ GeV, $p_T^{j2} > 45$ GeV
- $m_{jj} > 250$ GeV

Reversed Central Jet Veto (Control Region)

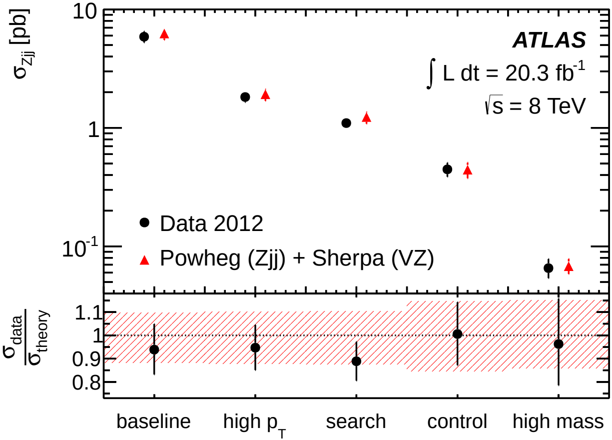


Central Jet Veto (Search Region)

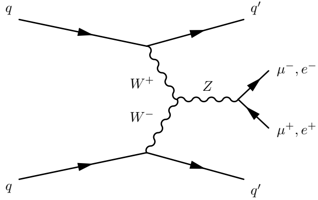


- Background only scenario excluded to $> 6\sigma$

Baseline	Z-Boson & $p_T^{j1} > 55$ GeV & $p_T^{j2} > 45$ GeV
High p_T	Baseline & $p_T^{j1} > 85$ GeV & $p_T^{j2} > 75$ GeV
High Mass	Baseline & $M_{jj} > 1$ TeV
Search and Control	As defined on previous slide



- WWZ vertex in VBF allows *space-like* access to TGCs
- Complimentary measurement to diboson analyses
- Utilise High-Mass region ($M_{jj} > 1$ TeV)
- 95% CL limits both with and without form factor Λ



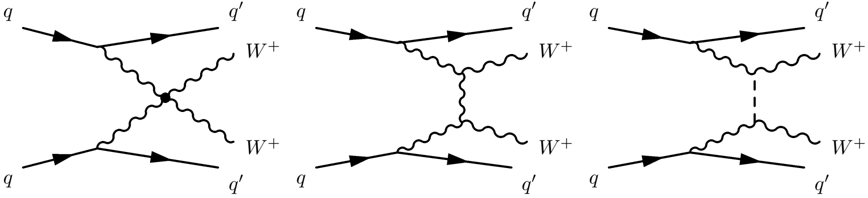
$$a(\hat{s}) = \frac{a_o}{(1 + \hat{s}/\Lambda^2)^2}$$

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

Motivation - 8 TeV, 20.3fb^{-1}

arxiv:1405.6241

- Longitudinal scattering of massive vector bosons violates unitarity without the Higgs
- Test of "Higgs in action", does $\sigma_{W^{\pm}W^{\pm}jj}$ scale with M_{WW}?

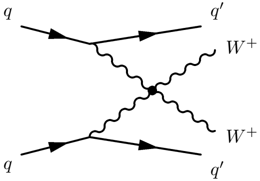


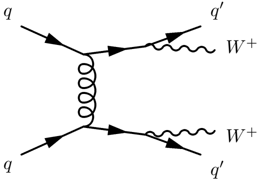
- Does the Higgs exactly unitarise the scattering?
- Sensitivity to quartic gauge couplings
- Same-sign $W^{\pm}W^{\pm}jj$ removes Born-level gluon-gluon initiated diagrams
- High-p_T, separated forward jets mean clean signature

Overview

- Two isolated leptons (e,μ), $p_T > 25$ GeV
- Missing $E_T > 40$ GeV
- 2 Jets, $p_T > 30$ GeV
- Veto 3rd looser lepton
- Dijet mass > 500 GeV
- INT: Interference between QCD & EWK

Electroweak (EWK) production



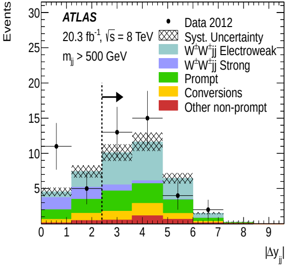


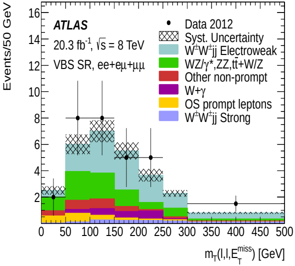
QCD production

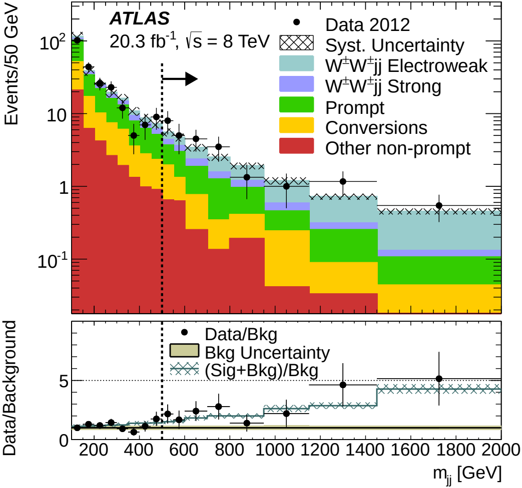
- Measure cross section in 2 phase-spaces:

	Phase Space Cuts	Signal Definition
Inclusive Region	as above	QCD & EWK & INT
VBS Region	as above & additional $\lvert\Delta y_{jj}\rvert > 2.4$	EWK & INT

$W^{\pm}W^{\pm}jj$ Plots







- Signal $W^{\pm}W^{\pm}jj$: SHERPA normalised to NLO POWHEG

$W^{\pm}W^{\pm}jj$ Cross Section Results

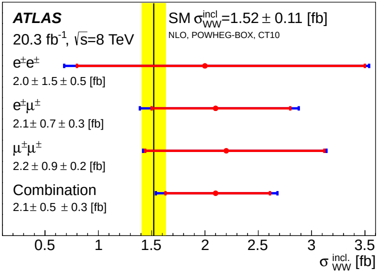
- Profile likelihood used to extract fiducial cross section from data
- Measured results all consistent with SM
- Expected fiducial cross section (NLO QCD,PowhegBox,Pythia,CT10):

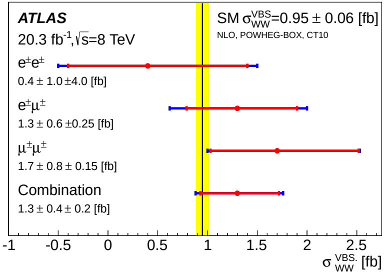
	Signal Definition	Fiducial Cross Section (fb)	Background Exclusion (σ)
Inclusive Region	QCD & EWK & INT	1.52 ± 0.11	3.4
VBS Region	EWK & INT	0.95 ± 0.06	2.8

- Measured fiducial cross sections results:

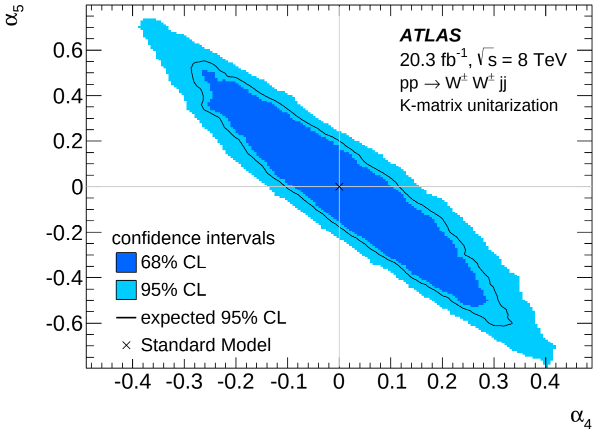
	Signal Definition	Fiducial Cross Section (fb)	Background Exclusion (σ)
Inclusive Region	QCD & EWK & INT	2.1 ± 0.5(stat.) ± 0.3(syst.)	4.5
VBS Region	EWK & INT	1.3 ± 0.4(stat.) ± 0.2(syst.)	3.6

Red bands: stats error Blue band: total error





- Use measured $W^{\pm}W^{\pm}jj$ cross section to put limits on aQGCs
- Parameterise low energy BSM effects with effective Lagrangian
- aQGC samples created using WHIZARD



Conclusion

- W^+W^- — 8 TeV, $\int Ldt = 20.3 fb^{-1}$
  - Cross section measured to $\pm 7.5\%$
  - 20% (2.1σ) high compared to SM
- $Z \rightarrow 4l$ — $7(8)$ TeV, $\int Ldt = 4.6(20.7) fb^{-1}$
  - Cross section measured to $\pm 10\%$
  - Branching ratio measured for s-channel
- *Electroweak Zjj* — 8 TeV, $\int Ldt = 20.3 fb^{-1}$
  - First observation at $> 6\sigma$
  - Cross section measured in 5 phase spaces
- $W^\pm W^\pm jj$ — 8 TeV, $\int Ldt = 20.3 fb^{-1}$
  - Cross section measured to 30%
  - Agreement with SM shows Higgs in action

Backup

Electroweak Zjj Phase Spaces

<table>
<tr><th>Object</th><th>baseline</th><th>high-mass</th><th>search</th><th>control</th><th>high-p_{T}</th></tr>
<tr><td>Leptons</td><td colspan="5">$|\eta^{\ell}| < 2.47,\ p_{\mathrm{T}}^{\ell} > 25\,\mathrm{GeV}$</td></tr>
<tr><td rowspan="2">Dilepton pair</td><td colspan="5">$81 \leq m_{\ell\ell} \leq 101\,\mathrm{GeV}$</td></tr>
<tr><td colspan="2">—</td><td colspan="2">$p_{\mathrm{T}}^{\ell\ell} > 20\,\mathrm{GeV}$</td><td>—</td></tr>
<tr><td rowspan="3">Jets</td><td colspan="5">$|y^{j}| < 4.4,\ \Delta R_{j,\ell} \geq 0.3$</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_1} > 55\,\mathrm{GeV}$</td><td>$p_{\mathrm{T}}^{j_1} > 85\,\mathrm{GeV}$</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_2} > 45\,\mathrm{GeV}$</td><td>$p_{\mathrm{T}}^{j_2} > 75\,\mathrm{GeV}$</td></tr>
<tr><td>Dijet system</td><td>—</td><td>$m_{jj} > 1\,\mathrm{TeV}$</td><td colspan="2">$m_{jj} > 250\,\mathrm{GeV}$</td><td>—</td></tr>
<tr><td>Interval jets</td><td colspan="2">—</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} = 0$</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} \geq 1$</td><td>—</td></tr>
<tr><td>Zjj system</td><td colspan="2">—</td><td>$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$</td><td>$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$</td><td>—</td></tr>
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Table 1. Summary of the selection criteria that define the fiducial regions. 'Interval jets' refer t the selection criteria applied to the jets that lie in the rapidity interval bounded by the dijet system

Fiducial region	σ_{fid} (pb)
baseline	5.88 ± 0.01 (stat) ± 0.62 (syst) ± 0.17 (lumi)
high-p_T	1.82 ± 0.01 (stat) ± 0.17 (syst) ± 0.05 (lumi)
high-mass	0.066 ± 0.001 (stat) ± 0.012 (syst) ± 0.002 (lumi)
search	1.10 ± 0.01 (stat) ± 0.09 (syst) ± 0.03 (lumi)
control	0.447 ± 0.004 (stat) ± 0.059 (syst) ± 0.013 (lumi)

Table 3. Fiducial cross sections for inclusive Zjj production, measured in the $Z \to \ell^+\ell^-$ decay channel.

Fiducial region	σ_{theory} (pb)
baseline	6.26 ± 0.06 (stat) $^{+0.50}_{-0.60}$ (scale) $^{+0.29}_{-0.35}$ (PDF) $^{+0.19}_{-0.25}$ (model)
high-p_T	1.92 ± 0.02 (stat) $^{+0.17}_{-0.20}$ (scale) $^{+0.09}_{-0.10}$ (PDF) $^{+0.05}_{-0.07}$ (model)
high-mass	0.068 ± 0.001 (stat) $^{+0.009}_{-0.009}$ (scale) $^{+0.004}_{-0.003}$ (PDF) $^{+0.004}_{-0.002}$ (model)
search	1.23 ± 0.01 (stat) $^{+0.11}_{-0.13}$ (scale) $^{+0.06}_{-0.07}$ (PDF) $^{+0.03}_{-0.04}$ (model)
control	0.444 ± 0.005 (stat) $^{+0.051}_{-0.054}$ (scale) $^{+0.021}_{-0.025}$ (PDF) $^{+0.032}_{-0.034}$ (model)

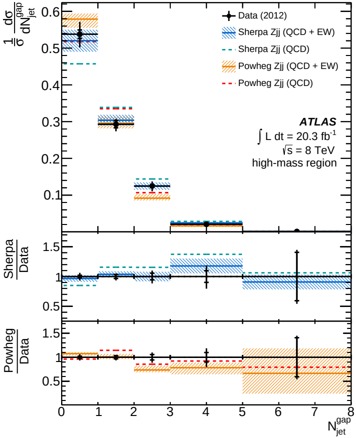
Table 4. Theory predictions for inclusive Zjj production cross sections in the $Z \to \ell^+\ell^-$ decay channel. The strong Zjj and electroweak Zjj events are produced using `Powheg`. A small contribution of ZV events, produced by `Sherpa`, is also included. The PDF uncertainty is estimated from the CT10 eigenvectors using the procedure described in ref. [21]. Scale and modelling uncertainties are each estimated from the envelope of `Powheg` sample variations discussed in section 4.

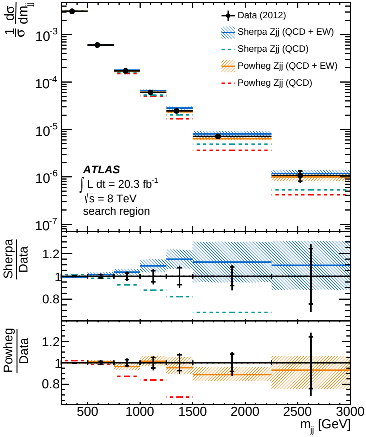
Yield Table

	Electron	Muon	Electron+muon
Data	14248	17938	32186
MC predicted N_{bkg}	$13700 \pm 1200\,^{+1400}_{-1700}$	$18600 \pm 1500\,^{+1900}_{-2300}$	$32600 \pm 2600\,^{+3400}_{-4000}$
MC predicted N_{EW}	$602 \pm 27 \pm 18$	$731 \pm 29 \pm 22$	$1333 \pm 50 \pm 40$
Fitted N_{bkg}	$13351 \pm 144 \pm 29$	$17201 \pm 161 \pm 31$	$30530 \pm 216 \pm 40$
Fitted N_{EW}	$897 \pm 92 \pm 27$	$737 \pm 98 \pm 28$	$1657 \pm 134 \pm 40$

Table 5. The number of strong (N_{bkg}) and electroweak (N_{EW}) Zjj events as predicted by the MC simulation and obtained from a fit to the data. The number of events in data is also given. The first and second uncertainties on the fitted yields are due to statistical uncertainties in data and simulation, respectively. The first and second uncertainties in the MC prediction are the experimental and theoretical systematic uncertainties, respectively.

- Unfolded plot of N_{jet}^{gap} and M_{jj}
- Fewer gap jets for *Electroweak Zjj*
- *Electroweak Zjj* M_{jj} obvious preference





aTGC Effective Lagrangian

$$
\begin{aligned}
\mathcal{L}_{eff}^{VWW}/g_{VWW} \quad = \quad & g_1^V V^\mu \left(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu} \right) \\
& + \kappa_V W_\nu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- \\
& + i g_5^V \epsilon_{\mu\nu\rho\sigma} \left[\left(\partial^\rho W^{-\mu} \right) W^{+\nu} - W^{-\mu} \left(\partial^\rho W^{+\nu} \right) \right] V^\sigma \\
& + i g_4^V W_\mu^+ W_\nu^- \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \\
& - \frac{\tilde{\lambda}_V}{2 m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}
\end{aligned} \tag{1}
$$

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

TABLE II: Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^{\pm}W^{\pm}jj$ electroweak prediction.

aQGC Lagrangians

- Extension of SM by additional dim-8 operators (no effect of TGCs)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- Electroweak Chiral Lagrangian

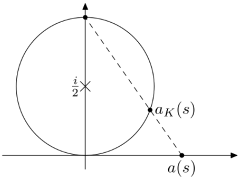
$$\mathcal{L}_4 = \alpha_4 \left(Tr\left[V_\mu V_\nu\right]\right)$$

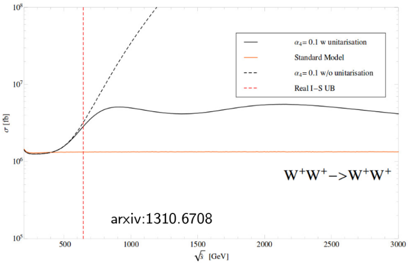
$$\mathcal{L}_5 = \alpha_5 \left(Tr\left[V_\mu V^\mu\right]\right)$$

K-Matrix Unitarisation

- aQGC signal samples were generated using K-Matrix unitarisation as implemented in WHIZARD
- for detailed description: see arxiv:0806.4145
- idea: project individual scattering amplitudes onto Argand circle to ensure unitarity

$\Rightarrow$ saturation of amplitude





- 95% 1D CL Limits

		Lower limit	Upper limit
α_4	expected	-0.10	0.12
	observed	-0.14	0.16
α_5	expected	-0.18	0.20
	observed	-0.23	0.24