Electroweak production of single vector bosons, vector boson scattering and triple gauge-boson production with the ATLAS detector

DIS2016

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on behalf of the ATLAS collaboration

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Physics motivation

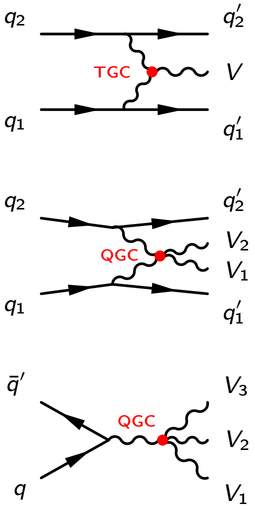
VBF, VBS and tri-boson production

- important test of SM's electroweak sector at TeV scale
- electroweak single vector boson production similar to VBF Higgs production
- VBS sensitive to EWSB mechanism
- gauge boson self-couplings fixed in SM

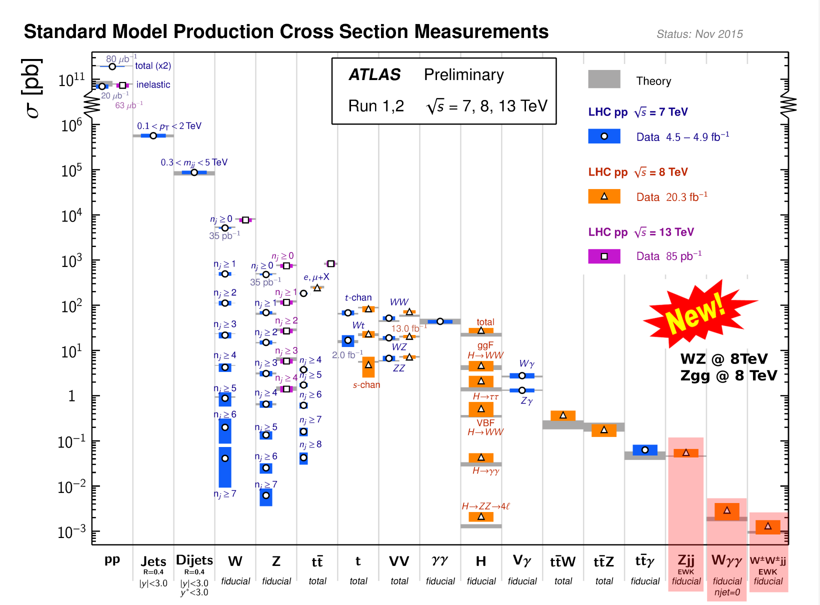
⇒ probe new physics through deviations

⇒ constrain aTGCs and aQGCs

- explore new final states never observed before



Today's menu

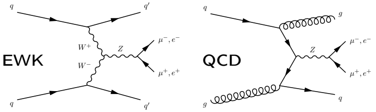

Standard Model Production Cross Section Measurements
Status: Nov 2015
σ [pb]
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 85 pb⁻¹
New!
WZ @ 8TeV
Zgg @ 8 TeV
total (x2)
inelastic
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
e, μ+X
t-chan
Wt
s-chan
WW
WZ
ZZ
total
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
pp
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ total
t total
VV total
γγ fiducial
H fiducial
Vγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial

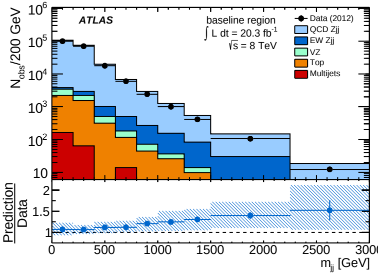
VBF Z production @ 8 TeV (JHEP04(2014)031)

- analysis used 20.3fb^{-1} at $\sqrt{s} = 8$ TeV
- five different fiducial regions defined to measure cross section of inclusive Zjj production
- cross section of electroweak Zjj production extracted in "search" region by fitting dijet invariant mass spectrum

$\Rightarrow$ allows to distinguish EWK component from much larger QCD background

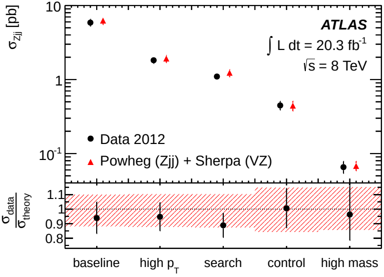
Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47,\ p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4,\ \Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}}^{\text{gap}} = 0$	$N_{\text{jet}}^{\text{gap}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	—

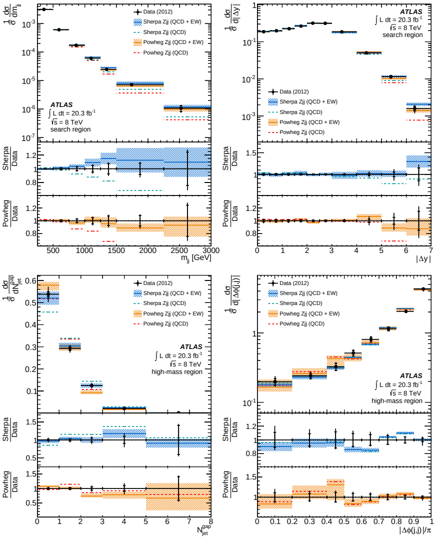




Inclusive *Zjj* production results

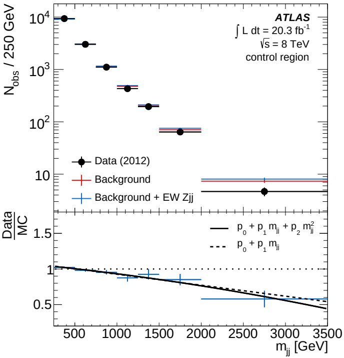
- fiducial cross section extracted from observed number of events
- results from e^+e^- and $\mu^+\mu^-$ channels consistent (max. discrepancy 1.1σ)
- differential cross section distributions obtained by iterative Bayesian unfolding
- m_{jj}, $|\Delta y_{jj}|$, $\Delta\phi_{jj}$, $N_{\text{jets}}^{\text{gap}}$, $p_{\text{T,balance}}$ in different regions

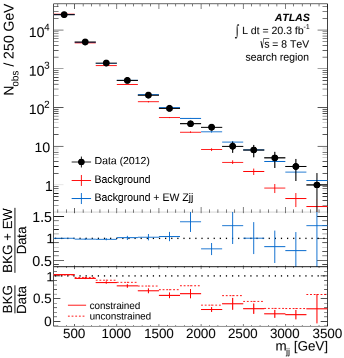




Extraction of electroweak *Zjj* production component

- template fit to invariant dijet mass spectrum in search region
- signal/background templates constructed from simulated events
- shape of background template reweighted to data in control region
- result: background-only hypothesis rejected with $> 5\sigma$
- $\sigma_{\text{EW}} = 54.7 \pm 4.6(\text{stat})\,^{+9.8}_{-10.4}(\text{syst}) \pm 1.5(\text{lumi})$ fb ($\sigma_{\text{EW}}^{\text{Powheg,NLO}} = 46.1 \pm 1.0$ fb)





VBS at the LHC

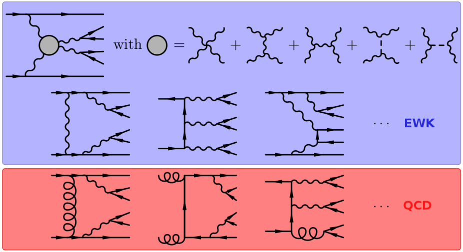
- final state for VBS at the LHC is *VVjj*

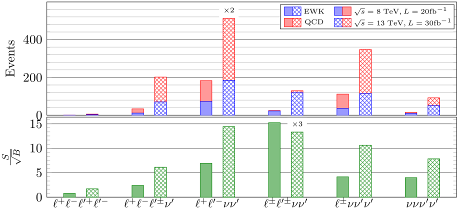
$\Rightarrow$ dijet system with high invariant mass and large separation in rapidity

- contributions from pure EWK diagrams but also diagrams with strong interactions

- final states with large EWK/QCD ratio have enhanced sensitivity to EWSB mechanism

$\Rightarrow$ $W^{\pm}W^{\pm}jj$ final state is most promising





calculated with Sherpa in a typical phase space at parton level

$W^\pm W^\pm jj$ production @ 8 TeV (Phys. Rev. Lett. 113, 141803)

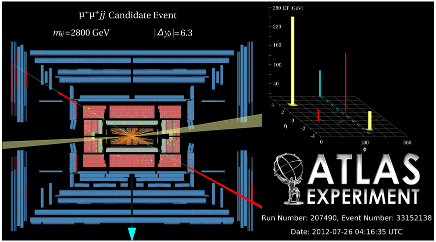
analysis used 20.3fb^{-1} at $\sqrt{s} = 8$ TeV
main selection criteria:

- 2 leptons (e, μ) of same charge
  $p_T \geq 25$ GeV, $|\eta| < 2.5$
- ≥ 2 jets, $p_T \geq 30$ GeV, $|\eta| < 4.5$
- $E_T^{miss} \geq 40$ GeV
- b-jet veto, 3rd lepton veto, Z veto
- $m_{jj} \geq 500$ GeV $\Rightarrow$ inclusive SR
- $+ \; |\Delta y_{jj}| > 2.4 \Rightarrow$ VBS SR

two signal regions:

- inclusive SR:
  treat full $W^\pm W^\pm jj$ process as signal
- VBS SR:
  - treat only EWK $W^\pm W^\pm jj$ as signal
  - set limits on aQGCs

signal topology



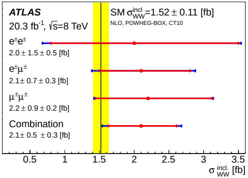
background validation in control regions

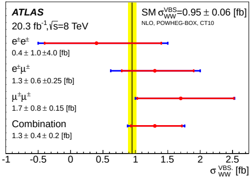
Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^\pm e^\pm$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^\pm \mu^\pm$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^\pm \mu^\pm$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

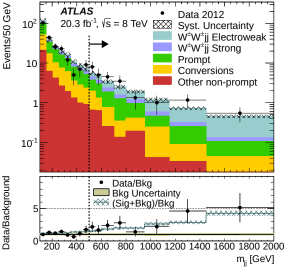
$W^{\pm}W^{\pm}jj$ production results (Phys. Rev. Lett. 113, 141803)

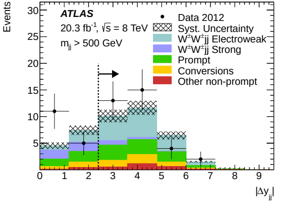
	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 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

- first significant observation of $W^{\pm}W^{\pm}jj$ production (4.5σ for full process, 3.6σ for EWK contribution)
- cross section extracted from event yields observed
- results limited by small data statistics









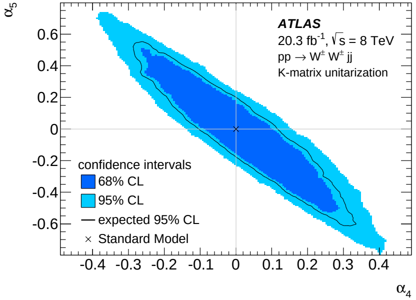
Interpretation: aQGC limits

- fiducial cross section measured in VBS SR compatible with prediction at 1σ level

$\Rightarrow$ constrain potential contributions from new physics

- framework: electroweak chiral Lagrangian with aQGC parameters α_4, α_5 and K-matrix unitarisation (JHEP 0811:010,2008)
- $\sigma_{\text{fid}}^{\text{EWK}}(\alpha_4, \alpha_5)$ calculated with Whizard + Pythia8
- observed 1D limits @ 95% CL:

$$\alpha_4 \in [-0.14, 0.16]$$
$$\alpha_5 \in [-0.23, 0.24]$$



WZjj production @ 8 TeV (arXiv:1603.02151)

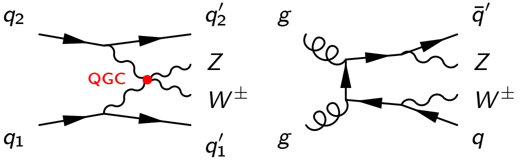
- *WZjj* production sensitive to VBS

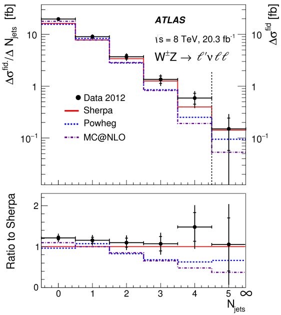
⇒ study electroweak *WZjj* production

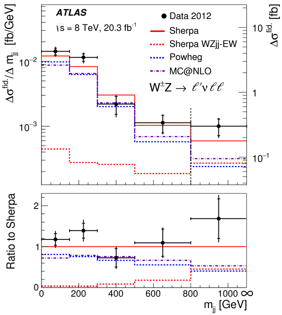
⇒ constrain aQGCs

- extend inclusive *WZ* analysis by requiring ≥ 2 jets with
  - $p_{\mathrm{T}} \geq 30$ GeV
  - $|\eta| < 4.5$
  - $m_{jj} \geq 500$ GeV

- aQGC SR:
  + $\Delta\phi(W, Z) \geq 2$
  + $\sum_{\ell} |p_{\mathrm{T}}| \geq 250$ GeV







Electroweak *WZjj* production and aQGC constraints

Selection	VBS	aQGC
Data	45	9
Total Expected	37.2 ± 1.1	4.9 ± 0.3
$WZjj$-EW	7.4 ± 0.2	1.1 ± 0.1
$WZjj$-QCD	20.8 ± 0.8	2.8 ± 0.3
tZ	3.0 ± 0.1	0.3 ± 0.0
Misid. leptons	2.5 ± 0.6	0.1 ± 0.1
ZZ	1.9 ± 0.3	0.2 ± 0.1
$t\bar{t} + V$	1.6 ± 0.1	0.3 ± 0.0

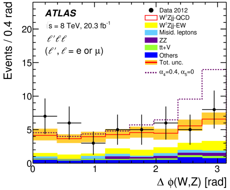
- expected sensitivity to electroweak *WZjj* production small

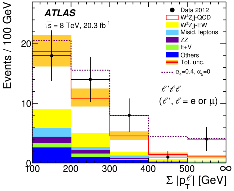
⇒ set upper limit on cross section in VBS phase space

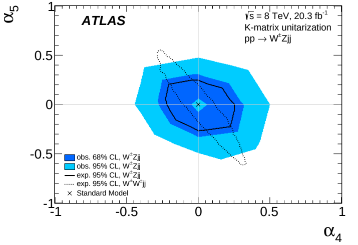
- $\sigma^{\text{fid}}_{WZjj\text{EWK}} \leq 0.67$ fb @ 95% CL
- SM prediction from VBFNLO: $\sigma^{\text{fid}}_{WZjj\text{EWK}} = 0.13 \pm 0.01$ fb

⇒ sensitivity to $\approx 5 \times \sigma_{\text{SM}}$

- aQGC parameters α_4, α_5 constrained by results in aQGC SR
- same framework as $W^{\pm}W^{\pm}jj$ analysis (Whizard, K-matrix)

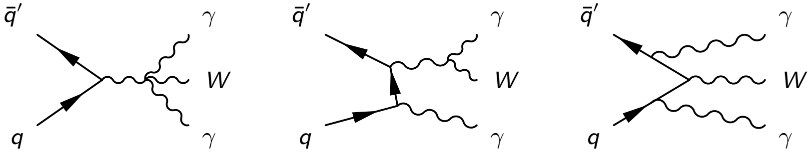






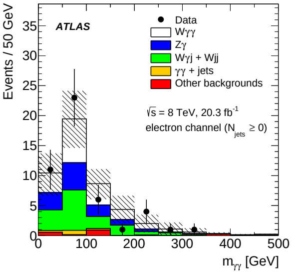
$W\gamma\gamma$ production @ 8 TeV (Phys. Rev. Lett. 115, 031802 (2015))

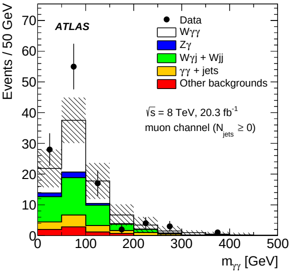
- measure fiducial cross section of $pp \to W(\ell\nu)\gamma\gamma + X$ using 20.3 fb^{-1} of ATLAS data collected at $\sqrt{s} = 8$ TeV
- measurement inclusive and exclusive in the number of jets
- use high diphoton mass region to constrain aQGC parameters



	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{\text{jet}} \geq 0$		$N_{\text{jet}} = 0$	
$W\gamma$j + Wjj	15.3 ± 4.8(stat.) ± 5.3(syst.)	30.5 ± 7.7(stat.) ± 6.8(syst.)	5.8 ± 2.1(stat.) ± 2.0(syst.)	14.4 ± 4.9(stat.) ± 4.9(syst.)
$\gamma\gamma$ + jets	1.5 ± 0.6(stat.) ± 1.0(syst.)	11.0 ± 4.0(stat.) ± 4.9(syst.)	0.2 ± 0.2(stat.) ± 0.2(syst.)	6.1 ± 3.5(stat.) ± 3.1(syst.)
$Z\gamma$	11.2 ± 1.1(stat.)	3.9 ± 0.2(stat.)	2.4 ± 0.5(stat.)	2.8 ± 0.2(stat.)
Other backgrounds	2.2 ± 0.6(stat.)	6.7 ± 2.0(stat.)	0.3 ± 0.1(stat.)	1.1 ± 0.3(stat.)
Total background	30.2 ± 5.0(stat.) ± 5.4(syst.)	52.1 ± 8.9(stat.) ± 8.4(syst.)	8.7 ± 2.2(stat.) ± 2.0(syst.)	24.4 ± 6.0(stat.) ± 5.8(syst.)
Data	47	110	15	53

Results on $W\gamma\gamma$ production





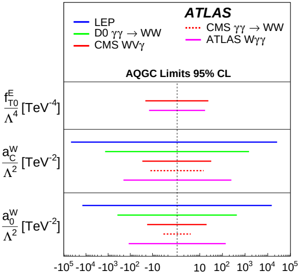
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

- combined significance in inclusive region $\geq 3\sigma$
- measurements in both channels compatible at 1σ level
- combined cross section in inclusive region 1.9σ above SM prediction @ NLO QCD, better agreement in exclusive region

Interpretation as limits on aQGC parameters

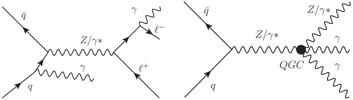
- high diphoton mass region $m_{\gamma\gamma} \geq 300$ GeV used to constrain aQGCs
- uses EFT approach with form-factor unitarisation (arXiv:1309.7890)
- study restricted to $f_{\{T0,M2,M3\}}/\Lambda^4$ ($f_{M2}, f_{M3} \leftrightarrow a_0^W, a_c^W$)
- fiducial cross sections with aQGCs calculated with VBFNLO
- form-factor scale $\Lambda_{FF} = 500$ GeV (600 GeV) for f_{T0}/Λ^4 ($f_{M2,3}/\Lambda^4$)

		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n = 1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n = 2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$

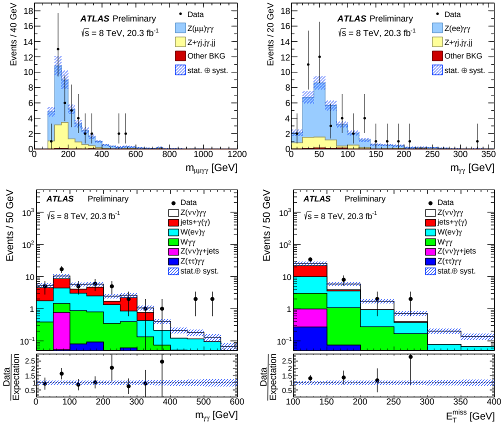


$Z\gamma\gamma$ production @ 8 TeV

- fiducial cross section measurement of $pp \to Z\gamma\gamma + X$ using 20.3fb^{-1} of ATLAS data collected at $\sqrt{s} = 8$ TeV using $Z \to \ell^+\ell^- / \nu\bar{\nu}$
- report fiducial cross sections for $N_{\text{jet}} \geq 0$ and $N_{\text{jet}} = 0$
- derive limits on aQGC parameters in high diphoton mass region and $N_{\text{jet}} = 0$

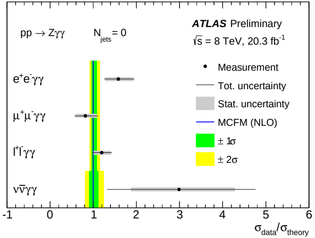


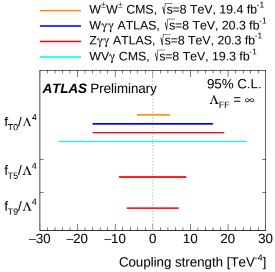
Cuts	$\ell^+\ell^-\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
Lepton	$p_{\text{T}}^{\ell} > 25$ GeV	-
	$\lvert\eta^{\ell}\rvert < 2.47$	-
Boson	$m_{\ell^+\ell^-} > 40$ GeV	$p_{\text{T}}^{\nu\bar{\nu}} > 110$ GeV
Photon	$E_{\text{T}}^{\gamma} > 15$ GeV	$E_{\text{T}}^{\gamma} > 22$ GeV
	$\lvert\eta^{\gamma}\rvert < 2.37$	
	$\Delta R(\ell, \gamma) > 0.4$	-
	$\Delta R(\gamma, \gamma) > 0.4$	$\Delta R(\gamma, \gamma) > 0.4$
	ϵ_h^p <0.5	
Jet	$p_{\text{T}}^{\text{jet}} > 30$ GeV, $\lvert\eta^{\text{jet}}\rvert < 4.5$	
	$\Delta R(\text{jet}, \ell/\gamma) > 0.3$	$\Delta R(\text{jet}, \gamma) > 0.3$
	Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$	

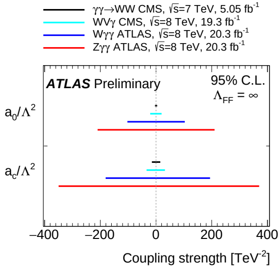


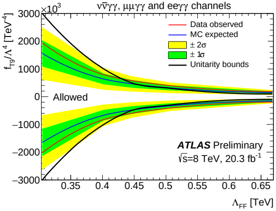
Results on $Z\gamma\gamma$ production and limits on aQGCs

- measured cross sections compatible with SM predictions
- aQGC limits in EFT approach with form factor unitarisation ($n = 2$)
- study restricted to $f_{\{\mathrm{T0,T5,T9,M2,M3}\}}/\Lambda^4$
- fiducial cross sections calculated with VBFNLO + Pythia8









Summary and outlook

- many ATLAS analyses covering wide range of electroweak physics
- high energy and large amount of data allow to study many electroweak processes for the first time

⇒ challenge theory predictions, improve limits on anomalous couplings

- still many interesting analyses on VBF and VBS from Run 1 in the pipeline
- 13 TeV data will improve measurement accuracies/allow for more detailed studies
- prospects at Run 2 are even better as signal cross section at high m_{jj} rises faster than backgrounds

⇒ stay tuned

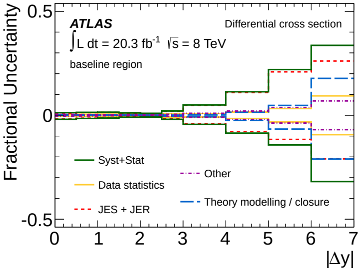
Backup

Zjj production: event selection

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_{T}*
Leptons	$\lvert\eta^{\ell}\rvert < 2.47$, $p_{\mathrm{T}}^{\ell} > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^{j}\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_{\mathrm{T}}^{j_1} > 55$ GeV				$p_{\mathrm{T}}^{j_1} > 85$ GeV
	$p_{\mathrm{T}}^{j_2} > 45$ GeV				$p_{\mathrm{T}}^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\mathrm{jet}}^{\mathrm{gap}} = 0$	$N_{\mathrm{jet}}^{\mathrm{gap}} \geq 1$	—
Zjj system	—		$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$	$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$	—

Zjj production: systematic uncertainties

Example for differential cross section



Electroweak *Zjj* production cross section

Source	ΔN_{EW} Electrons	ΔN_{EW} Muons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Electrons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Muons
Lepton systematics	—	—	±3.2 %	±2.5%
Control region statistics	±8.9 %	±11.2 %	—	—
JES	±5.6 %		$^{+2.7}_{-3.4}$ %	
JER	±0.4 %		±0.8 %	
Pileup jet modelling	±0.3 %		±0.3 %	
JVF	±1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	±8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	±7.5 %		—	
Signal/background interference	±6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		±0.1 %	

$W^{\pm}W^{\pm}jj$ production: event selection

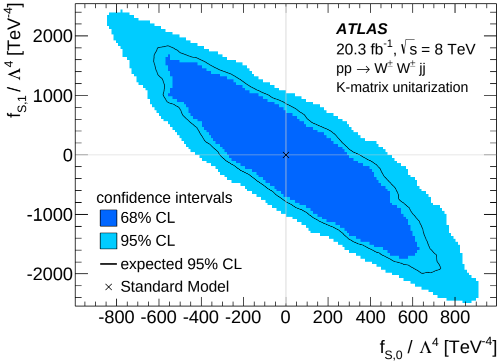
1. event cleaning
2. exactly two selected leptons with $m_{\ell\ell'} \geq 20$ GeV
3. veto events with additional veto leptons
4. $q_{\ell_1} \times q_{\ell_2} > 0$
5. $|m_{ee} - m_Z| > 10$ GeV in the ee-channel
6. $E_{\mathrm{T}}^{\mathrm{miss}} \geq 40$ GeV
7. at least two jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.5$
8. $m_{jj} \geq 150$ GeV
9. b-jet veto @70% using the MV1 tagger
10. $m_{jj} \geq 500$ GeV - Inclusive analysis region
11. $\Delta y_{jj} > 2.4$ - VBS analysis region

$W^{\pm}W^{\pm}jj$ production: systematic uncertainties

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background		Signal	
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^{\pm}W^{\pm}jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^{\pm}W^{\pm}jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

$W^\pm W^\pm jj$ production: converted aQGC limits



conversion taken from arxiv:1309.7890 (Eq 60 + 61)

$$\frac{f_{S0}}{\Lambda^4} = \frac{8}{v^4}\alpha_4 \qquad \frac{f_{S1}}{\Lambda^4} = \frac{8}{v^4}(\alpha_4 + 2\alpha_5)$$

$W^{\pm}Zjj$ production: event selection

Variable	Total	Fiducial and aTGC	VBS	aQGC
Lepton $\|\eta\|$	—	< 2.5	< 2.5	< 2.5
p_{T} of ℓ_Z, p_{T} of ℓ_W [GeV]	—	> 15, > 20	> 15, > 20	> 15, > 20
m_Z range [GeV]	$66 - 116$	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$
m_{T}^{W} [GeV]	—	> 30	> 30	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	> 0.2, > 0.3	> 0.2, > 0.3	> 0.2, > 0.3
p_{T} two leading jets [GeV]	—	—	> 30	> 30
$\|\eta_j\|$ two leading jets	—	—	< 4.5	< 4.5
Jet multiplicity	—	—	≥ 2	≥ 2
m_{jj} [GeV]	—	—	> 500	> 500
$\Delta R(j, \ell)$	—	—	> 0.3	> 0.3
$\|\Delta\phi(W, Z)\|$	—	—	—	> 2
$\sum \|p_{\mathrm{T}}^{\ell}\|$ [GeV]	—	—	—	> 250

$W^{\pm}Zjj$ production: systematic uncertainties

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Source	Relative uncertainties [%]				
e energy scale	0.8	0.4	0.4	0.0	0.3
e id. efficiency	2.9	1.8	1.0	0.0	1.0
μ momentum scale	0.0	0.1	0.1	0.1	0.1
μ id. efficiency	0.0	0.7	1.3	2.0	1.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.3	0.2	0.2	0.1	0.3
Trigger	0.1	0.1	0.2	0.3	0.2
Pileup	0.3	0.2	0.2	0.1	0.2
Misid. leptons background	2.9	0.9	3.1	0.9	1.3
ZZ background	0.6	0.5	0.6	0.5	0.5
Other backgrounds	0.7	0.7	0.7	0.7	0.7
Uncorrelated	0.7	0.6	0.5	0.5	0.3
Total systematics	4.5	2.6	3.7	2.5	2.4
Luminosity	2.2	2.2	2.2	2.2	2.2
Statistics	6.2	5.4	5.3	4.7	2.7
Total	8.0	6.3	6.8	5.7	4.2

$W\gamma\gamma$ production: event selection

Selection criteria	$e\nu\gamma\gamma$	$\mu\nu\gamma\gamma$
Lepton p_{T}	$p_{\mathrm{T}}^{e} > 20\,GeV$	$p_{\mathrm{T}}^{\mu} > 20\,GeV$
Lepton η	$\lvert\eta_e\rvert < 2.47$	$\lvert\eta_\mu\rvert < 2.4$
	excl. $1.37 < \lvert\eta_e\rvert < 1.52$	
W transverse mass	$m_{\mathrm{T}} > 40\,GeV$	
Missing E_{T}	$> 25\,GeV$	
Lepton track isolation	$p_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.2) < 0.15\,p_{\mathrm{T}}^{\mathrm{lepton}}$	
Lepton calo isolation	$E_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.2) < 0.20\,p_{\mathrm{T}}^{\mathrm{lepton}}$	–
Lepton $\lvert d_0\rvert/\sigma(d_0)$	< 6	< 3
Lepton $\lvert z_0 \cdot \sin\theta\rvert$	< 0.5 mm	
Photons	$E_{\mathrm{T}}^{\gamma} > 20\,GeV$	
	$\lvert\eta_\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$)	
	$\Delta R(l,\gamma) > 0.7$	
	$\Delta R(\gamma,\gamma) > 0.4$	
	$E_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.4) < 4\,GeV$	
Z rejection cuts	$m(e\gamma\gamma) - m(Z) < -10\,GeV$ or $> 5\,GeV$	–
	$m(e\gamma_1) - m(Z) < -10\,GeV$ or $> 3\,GeV$	–
	$m(e\gamma_2) - m(Z) < -5\,GeV$ or $> 3\,GeV$	–
	$p_{\mathrm{T}}(e\gamma\gamma) > 30\,GeV$	–
	inclusive: $\mathrm{N_{jet}} > 0$; exclusive: $\mathrm{N_{jet}} = 0$	
Jet	anti-k_t with R=0.4	
	$p_{\mathrm{T^{jet}}} > 30\,GeV$, $\lvert\eta^{\mathrm{jet}}\rvert < 4.4$	
	$\Delta R(\mathrm{lepton}/\gamma, \mathrm{jet}) > 0.3$	
	jet vertex fraction > 0.5 for jets with $p_{\mathrm{T}} < 50\,GeV$ and $\lvert\eta\rvert < 2.4$	

$W\gamma\gamma$ production: systematic uncertainties

	Inclusive Selection	Exclusive Selection
Correction Factor ϵ	$(40.4 \pm 0.7$ (stat.)) %	$(39.7 \pm 1.0$ (stat.)) %
Acceptance A	$(89.2 \pm 0.3$ (stat.)) %	$(89.7 \pm 0.4$ (stat.)) %
Efficiency C	$(45.2 \pm 0.8$ (stat.)) %	$(44.3 \pm 1.1$ (stat.)) %
Relative systematic error on the efficiency C [%]		
Systematic Source	syst. unc.	syst. unc.
Muon Eff Scale Factor	0.0	0.0
Muon Energy Scale	0.3	0.3
Muon Isolation Eff.	0.2	0.1
Muon Resolution ID	0.1	0.1
Muon Resolution MS	2.1	1.4
Photon Energy Scale	1.0	1.1
Photon Energy Resol.	0.3	0.5
Photon ID Efficiency	0.8	0.9
MET Reso Soft Terms	0.4	0.8
MET Scale Soft Terms	1.0	1.1
Jet Energy Scale	3.2	6.0
Jet Energy Resolution	0.8	1.4
Jet Vertex Fraction	–	0.3
Pileup reweight	0.0	0.5
Trigger	0.5	0.5
Total rel. syst. error on C [%]	4.3	6.7

	Inclusive Selection	Exclusive Selection
Correction Factor ϵ	$(19.6 \pm 0.5$ (stat.)) %	$(15.1 \pm 0.7$ (stat.)) %
Acceptance A	$(82.5 \pm 0.4$ (stat.)) %	$(82.5 \pm 0.6$ (stat.)) %
Efficiency C	$(23.7 \pm 0.6$ (stat.)) %	$(18.4 \pm 0.8$ (stat.)) %
Relative systematic error on the efficiency C [%]		
Systematic Source	syst. unc.	syst. unc.
Electron Reconstruction Eff.	0.1	0.1
Electron ID Uncert	0.2	0.2
Electron Isolation Eff.	0.0	0.0
EM Energy Scale	2.4	4.5
EM Energy Resolution	0.3	0.3
Photon ID Eff	0.8	0.9
MET Reso Soft Terms	0.6	1.2
MET Scale Soft Terms	0.3	1.3
Jet Energy Resol	1.5	1.4
Jet Energy Scale	5.3	6.2
Jet Vertex Fraction	–	0.4
Pileup Reweighting	0.2	0.2
Trigger	0.7	0.7
Total rel. syst. error on C [%]	6.2	8.2

Phase space for comparison plot on slide 7

The phase space used to calculate the fiducial cross sections with SHERPA given in Table 4.1 is defined at parton level as follows. Charged leptons must have a transverse momentum of $p_{\mathrm{T}} \geq 25$ GeV and lie within $|\eta| \leq 2.5$. All charged leptons must be separated from each other by $\Delta R \geq 0.3$ and the minimum invariant mass of all charged lepton pair combinations must satisfy $m_{\ell\ell} \geq 20$ GeV. In addition, at least two jets, reconstructed with the anti-k_t algorithm using a radius parameter of 0.4 from all outgoing partons, with $p_{\mathrm{T}} \geq 30$ GeV and $|\eta| \leq 4.5$ are required. Leptons and jets must be separated in ΔR by more than 0.3. Furthermore, the invariant mass of the two outgoing jets must satisfy $m_{jj} \geq 500$ GeV and they need to be separated in rapidity by more than 2.4.

Sherpa version 1.4.5 was used