Measurement of multi-boson production with the ATLAS detector

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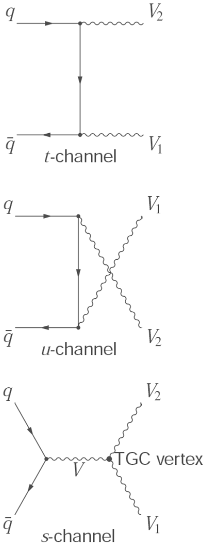
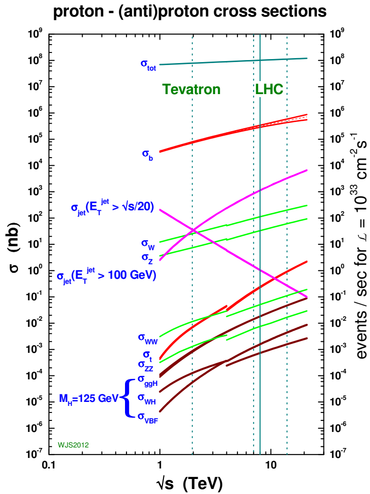
Multiboson production at the LHC



- Test of the **Standard Model**: electroweak; pQCD
- Background to **Higgs & BSM** searches
- **Anomalous gauge couplings** ⇒ new physics in EW sector

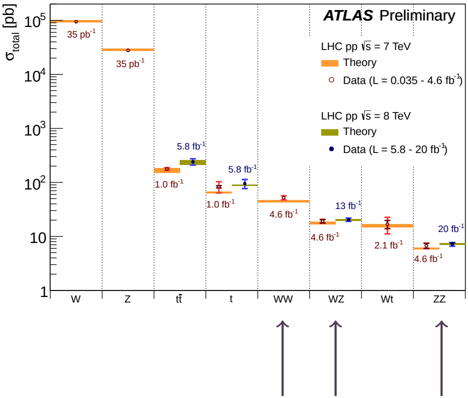
Multiboson production at the LHC



- Test of the **Standard Model**: electroweak; pQCD
- Background to **Higgs & BSM** searches
- **Anomalous gauge couplings** ⇒ new physics in EW sector
- Small cross sections → profit from **high energy, high luminosity**

`http://www.hep.ph.ic.ac.uk/~wstirlin/plots/crosssections2012_v5.pdf`
W.J. Stirling, private communication

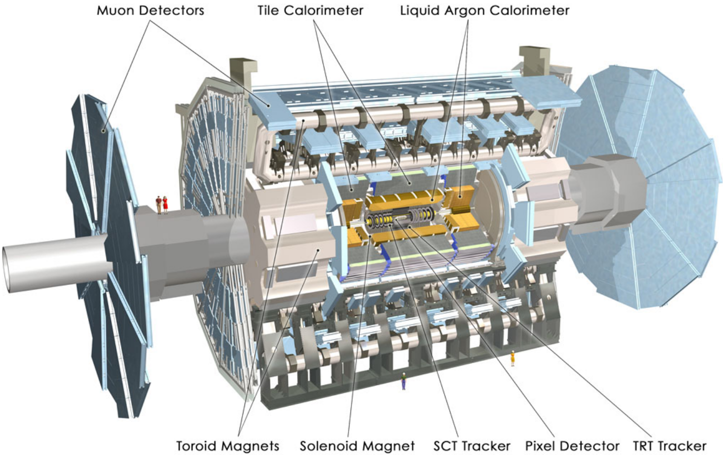
Weak boson production - Probing the SM over five orders of magnitude



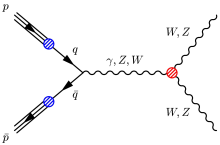
- **WW $\rightarrow \ell\nu\ell\nu$**
  Phys.Rev. D87, 112001 (2013)
- **WZ $\rightarrow \ell\ell\ell\nu$**
  ATLAS-CONF-2013-021
- **ZZ $\rightarrow 4\ell$ and ZZ $\rightarrow \ell\nu\ell\nu$**
  JHEP03 (2013) 128,
  ATLAS-CONF-2013-020
- **WW/WZ $\rightarrow \ell\nu$jj**
  ATLAS-CONF-2012-157
- **Wγ, Zγ**
  Phys. Rev. D 87, 112003 (2013)
- **Prospects at 14 TeV**
  ATL-PHYS-PUB-2012-005,
  ATL-PHYS-PUB-2013-006

(latest publications)

ATLAS detector



Anomalous gauge couplings



SM charged TGC; no neutral TGC

BSM modelled by **effective Lagrangian** with anomalous TGC parameters

5 charged couplings:

$g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z$, and λ_γ

SM case:

$g_1^Z = \kappa_Z = \kappa_\gamma = 1$;

$\lambda_Z = \lambda_\gamma = 0$

8 neutral couplings:

$h_3^V, h_4^V, f_4^V, f_5^V$ with $V = Z, \gamma$

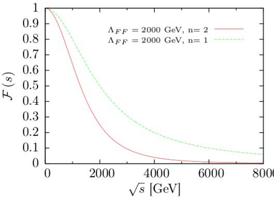
all $h_i^V = 0$ in SM

Parameters' accessibility by channel:

aTGC vertex	parameters	channel
WWγ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW, Wγ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW, WZ
ZZγ	h_3^Z, h_4^Z	ZZ
Z$\gamma\gamma$	h_3^γ, h_4^γ	Zγ
ZγZ	f_{40}^Z, f_{50}^Z	Zγ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Amplitudes can **violate unitarity** $\rightarrow$ apply **form factor** to coupling f as

$f_i^V = f_{i,0}^V/(1 + \hat{s}/\Lambda^2)^n$



O. Schlimpert, 2013

$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

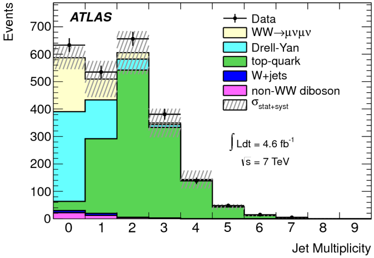
$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6\,\mathrm{fb}^{-1}$: Phys.Rev. D87, 112001 (2013)

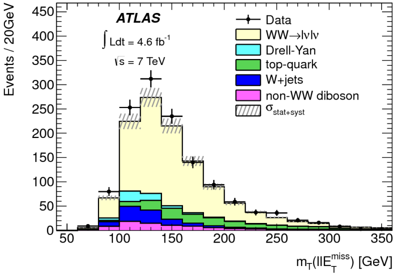
Selection:

- 2 high-p_T isolated leptons (opposite charge)
- Z-veto to suppress Drell-Yan: $|m_{ll} - m_Z| > 15, 10\,\mathrm{GeV}(ee, \mu\mu)$
- $E_{T,Rel}^{miss} > 45{,}45{,}25\,\mathrm{GeV}(ee, e\mu, \mu\mu)$

$$E_{T,Rel}^{miss} = \begin{cases} E_T^{miss} \cdot \sin\Delta\Phi, & \text{if } \Delta\Phi < \pi/2 \\ E_T^{miss}, & \text{if } \Delta\Phi \geq \pi/2 \end{cases}$$

- jet veto to suppress top background





$m_T(llE_T^{miss})$ in signal region

Background estimates

top	data-driven (b-tagged)
W+jets	data-driven (fakes)
Drell-Yan	transfer-factor Drell-Yan control region

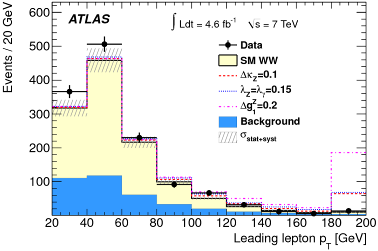
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

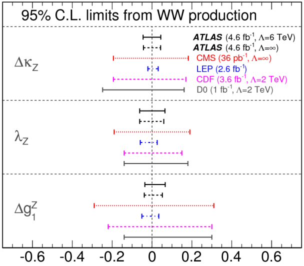
$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6\,\mathrm{fb}^{-1}$: Phys.Rev. D87, 112001 (2013)

Results

	events
Top	141±30±22
W+jets	98±2±43
Drell-Yan	51±7±12
Other dibosons	78 ±2±10
Bkg (total)	369±31±53
Signal expected	824±4±69
Total data	1325

Measured:
$\sigma = 51.9 \pm 2.0(\mathrm{stat}) \pm 3.9(\mathrm{syst}) \pm 2.0(\mathrm{lumi})$ pb
Theory: $\sigma = 44.7^{+2.1}_{-1.9}$ pb
Dominated by **systematics**
(main uncertainty: jet veto efficiency)





Limits on charged aTGC for *WWZ* and $WW\gamma$ (LEP scenario)

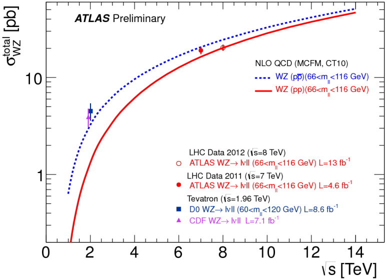
WZ $\rightarrow \ell\ell\ell\nu$

$\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 13\,\mathrm{fb}^{-1}$: ATLAS-CONF-2013-021

Event selection:
3 high-p_T isolated leptons, large $E_\mathrm{T}^\mathrm{miss}$ and m_T^W

Backgrounds

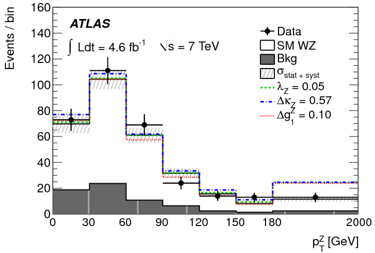
Z+jets, top: data-driven (fake leptons)
ZZ, W/Z + γ: from simulation



Measured total cross section:
$\sigma =$
$20.3^{+0.8}_{-0.7}(\mathrm{stat})\ ^{+1.2}_{-1.1}(\mathrm{syst})\ ^{+0.7}_{0.6}(\mathrm{lumi})$ pb
Theory: $\sigma = 20.3 \pm 0.8$ pb
Dominated by **systematics**

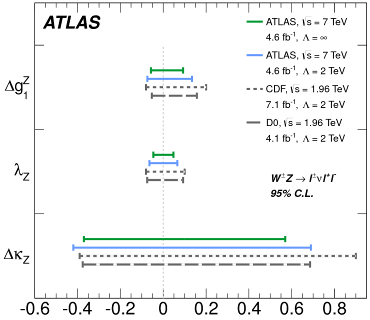
$\mathbf{WZ} \to \ell\ell\ell\nu$

$\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 13\,\mathrm{fb}^{-1}$: ATLAS-CONF-2013-021



Extraction of aTGC limits from $p_{\mathrm{T}}(\mathrm{Z})$ spectrum

aTGC (from $\sqrt{s} = 7\,\mathrm{TeV}$)

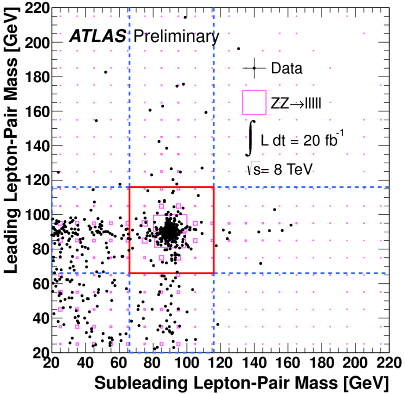


ZZ $\to 4\ell$

$\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20\,\mathrm{fb}^{-1}$: ATLAS-CONF-2013-020

Event selection:
4 leptons very clean channel

- 4 isolated leptons
- combined to same-flavor, opposite charge pairs
- Z-mass window



Dominant background: $W^\pm/Z + X$ ($X = \gamma$ or jets - misidentified)
Fake estimate (data-driven)

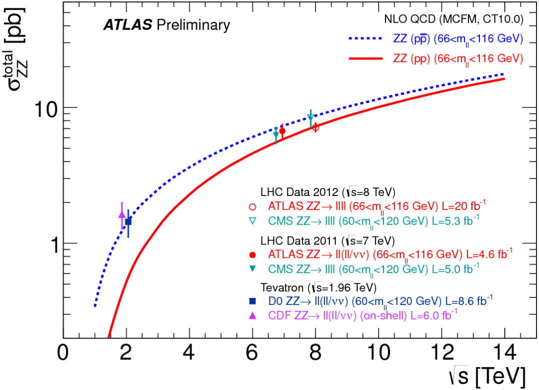
Signal yields:
Data events: **305**
Signal expectation: **292.5** $\pm$**10.6**
Background expectation: **20.4** $\pm$ **5.8**

"golden channel"

$ZZ \to 4\ell$

$\sqrt{s} = 8\,\text{TeV},\ \mathcal{L} = 20\,\text{fb}^{-1}$: ATLAS-CONF-2013-020

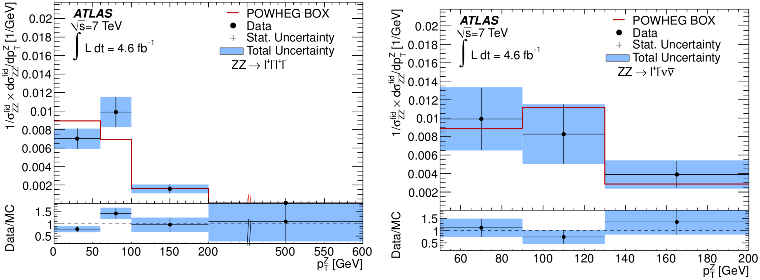
Measured total cross section:
$\sigma_{ZZ}^{tot} =$
$7.1^{+0.5}_{-0.4}(stat) \pm 0.3(syst) \pm 0.2(lumi)$ pb
Theory: $\sigma = 7.2^{+0.3}_{-0.2}$ pb
Dominated by **statistics**



$ZZ \to \ell\ell\nu\nu$

$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6\,\mathrm{fb}^{-1}$: JHEP03 (2013) 128

Event selection:
2 leptons: same flavor, in Z-window
$E_{\mathrm{T}}^{\mathrm{miss}}$ fraction cut
third lepton veto

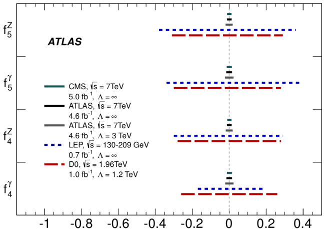


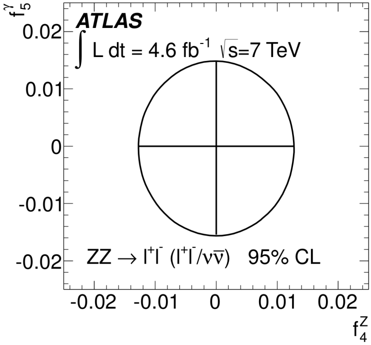
$ZZ \to \ell\ell\nu\nu$ and $ZZ \to 4\ell$

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.6\,\text{fb}^{-1}$: JHEP03 (2013) 128

Combination and limits on neutral aTGC

Using $p_{\mathrm{T}}(\mathrm{Z})$ spectrum for limit extraction





WW/WZ in the single lepton final state

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.7\,\text{fb}^{-1}$: ATLAS-CONF-2012-157

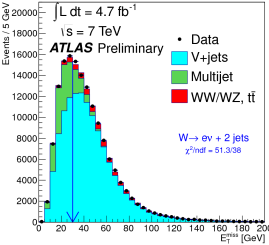
Semi-leptonic WW/WZ $\rightarrow \ell\nu qq'$

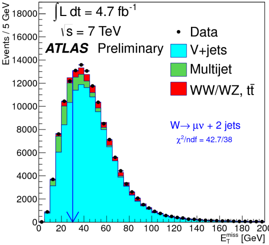
+larger branching ratio

−large background from W/Z+jets

Event selection:
one high-p_T isolated lepton, E_T^{miss}, $m_T(\ell, E_T^{\text{miss}})$
2 jets, well separated

Dominating background **W/Z+jets:**
Estimated from data





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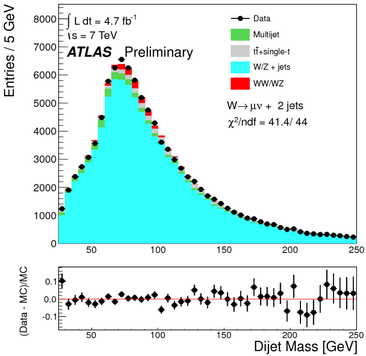
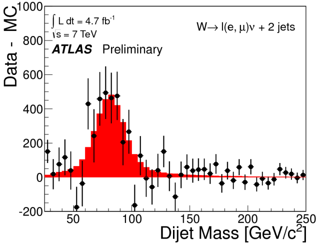
WW/WZ in the single lepton final state

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.7\,\text{fb}^{-1}$: ATLAS-CONF-2012-157



fit to m_{jj} spectrum $\rightarrow$ extract cross section



Measured:
$\sigma = 72 \pm 9\,(\text{stat}) \pm 15\,(\text{syst}) \pm 13\,(\text{MC stat})$ pb
Theory: $\sigma = 63.4 \pm 2.6$ pb Dominated by **systematics** (JES)

W/Z resonance observed with 3.3 σ

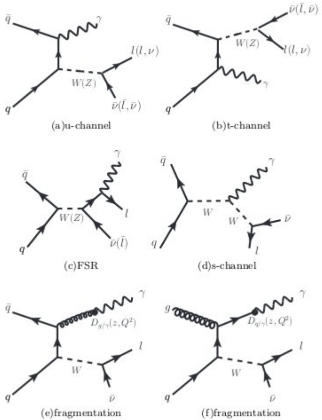
Wγ, Zγ

$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6,\mathrm{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$

Example here: $\mathbf{Z\gamma \to \ell^+\ell^-\gamma}$

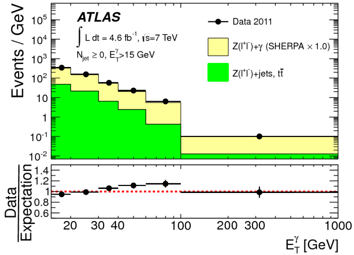
$Z\gamma \to \ell^+\ell^-\gamma$ selection:
two opposite-sign same-flavor leptons,
m_{ll} cut
isolated γ
$\Delta R(\gamma, \ell) > 0.7$ to suppress FSR photons



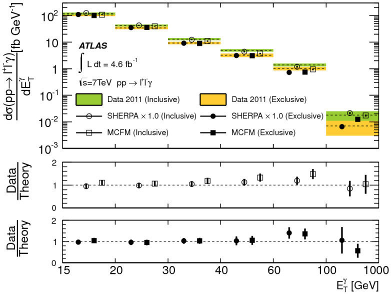
probe the non-Abelian $SU(2)_L \times U(1)_Y$ gauge boson self-couplings

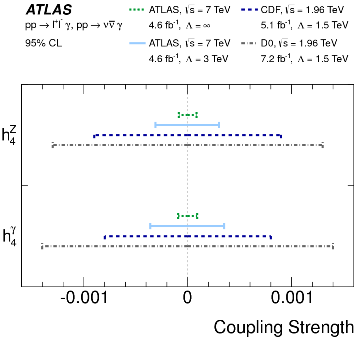
$W\gamma, Z\gamma$

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.6,\text{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)



aTGC limits extracted from E_T^{γ}





Vector boson scattering and triboson production at 14 TeV

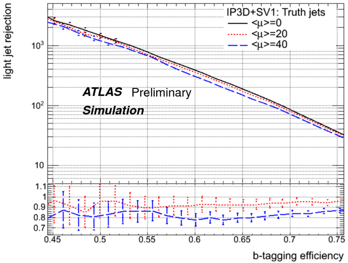
ATL-PHYS-PUB-2012-005, ATL-PHYS-PUB-2013-006

Sensitivity of the **high-luminosity LHC:** (14 TeV, 300...3000 fb^{-1}) to Vector Boson Scattering and Triboson production
$\rightarrow$ Expected limits to anomalous quartic gauge couplings

Pile-up	increase at higher instantaneous lumi
Backgrounds	modelled from MC
Optimization	no detailed optimization

Shower & simulation of detector response

Full-simulation samples for upgraded ATLAS $\rightarrow$ model pile-up dependence of efficiencies and resolutions



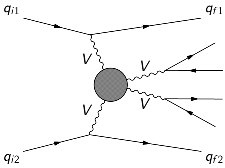
(Example: b-tagging performance vs. pile-up)

VBS in $W^\pm W^\mp jj \to \ell\nu\ell\nu jj$ channel

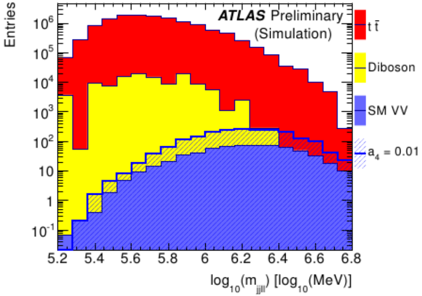
Model Pythia; aQGC parameter $\alpha_5 = 0$, vary α_4

Background $t\bar{t}$, diboson

Selection
- 2 different flavor, opposite charge leptons
- $\geq$ 2 highp_T, forward jets
- large E_T^{miss}



Extraction of limits with templates for the m_{jjll} mass (since reconstruction of m_{WW} not possible)



Upper Limits @ 95% CL according to lumi:

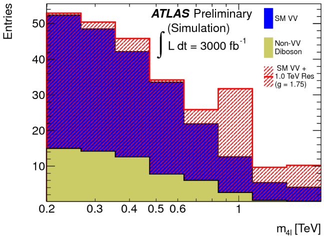
lumi	α_4^{UL}
300 fb^{-1}	0.066
1000 fb^{-1}	0.025
3000 fb^{-1}	0.016

Sensitivity in $ZZ \to 4\ell$ channel

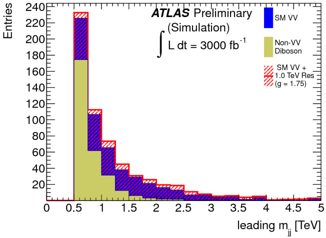
MC generator Whizard

Selection
- ≥ 2 jets with $m(jj) > 1$ TeV
- 4 leptons, divided in two opposite-sign, same-flavor pairs

(very clean channel)



$m_{4\ell}$ spectrum



m_{jj} distribution

Tensor singlet resonance with different mass, coupling, and width

mass	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	1.0	2.1 GeV	2.4σ	7.5σ
1 TeV	1.75	50.4 GeV	1.7σ	$5.5\ \sigma$
1 TeV	2.5	102.7 GeV	3σ	9.4σ

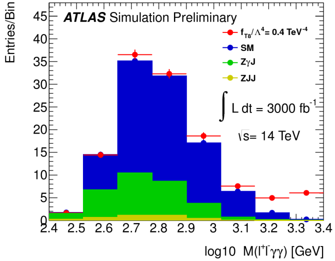
Triboson production at 14 TeV: $Z\gamma\gamma$

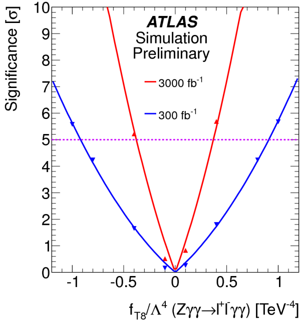
MC generator MadGraph 1.5.10

Selection
- 2 opposite-charge, same-flavor high-p_T leptons in Z-window
- 2 photons, well separated
- one lepton and one γ with $p_T > 160\,\text{GeV}$ (improves aQGC sensitivity)

Background $Z\gamma j$, Zjj through jet $\to\gamma$ fake rate

allows full reconstruction of $Z\gamma\gamma$ invariant mass:





5σ-significance discovery values:

	$300\,\text{fb}^{-1}$	$3000\,\text{fb}^{-1}$
f_{T8}/Λ^4	$0.9\,\text{TeV}^{-4}$	$0.4\,\text{TeV}^{-4}$
f_{T8}/Λ^4	$2.0\,\text{TeV}^{-4}$	$0.7\,\text{TeV}^{-4}$

Conclusions & Outlook

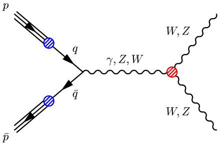
- Measurements of diboson production in various channels
- Good agreement with theoretical predictions at NLO-QCD
- Results start to be dominated by systematics
- Limits on aTGC competitive to LEP limits
- After the upgrade, VBS and triboson production will gain importance

References

Channel	$\sqrt{s}$ /TeV (year)	Lumi /fb^{-1}	publication
WW$\rightarrow \ell\nu\ell\nu$			
	7 (2010)	0.034	Phys.Rev.Lett.107 (2011) 041802 arXiv:1104.5225
	7 (2011)	1.02	Physics Letters B 712 (2012) 289-308 arXiv:1203.6232
	7 (2011)	4.6	Phys.Rev. D87, 112001 (2013) arXiv:1210.2979
WZ $\rightarrow \ell\ell\ell\nu$			
	7 (2011)	1.02	Phys.Lett.B709 (2012) 341-357 arXiv:111.5570
	7 (2011)	4.6	Eur.Phys.J.C (2012) 72:2173 arXiv:1208.1390
	8 (2012)	13	ATLAS-CONF-2013-021
ZZ $\rightarrow 4\ell$			
	7 (2011)	1.02	Phys.Rev.Lett. 108 (2012) 041804 arXiv:1110.5016
	8 (2012)	20.3	ATLAS-CONF-2013-020
ZZ $\rightarrow 4\ell + \ell\ell\nu\nu$			
	7 (2011)	4.6	JHEP03 (2013) 128 arXiv:1211.6096
WW/WZ$\rightarrow \ell\nu jj$			
	7 (2011)	4.7	ATLAS-CONF-2012-157
Wγ/Zγ	7 (2010)	0.035	JHEP 1109 (2011) 072 arXiv:1106.1592
	7 (2011)	4.6	Phys. Rev. D 87, 112003 (2013) arXiv:1302.1283

BACKUP SLIDES

Anomalous gauge couplings



SM charged TGC; no neutral TGC

BSM e.g. extended Higgs sector, additional vector bosons (W'), Technicolor, etc.

Effective Lagrangian for Triple Gauge Couplings

- $SU(2)xU(1)$ gauge group governs the structure of TGC
- Effective Lagrangian with triple gauge couplings can be constructed
- Amplitudes can violate unitarity → apply form factor to coupling f as $f_i^V = f_{i,0}^V/(1+\hat{s}/\Lambda^2)^n$

Accounting for gauge invariance, this reduces to:

5 charged couplings:

$g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z$, and λ_γ

(SM case: $\Delta g_1^Z = \Delta\kappa_Z = \Delta\kappa_\gamma = \lambda_Z = \lambda_\gamma = 0$)

8 neutral couplings:

$h_3^V, h_4^V, f_4^V, f_5^V$ with $V = Z, \gamma$

all $h_i^V = 0$ in SM

Parameters accessibility by channel:

aTGC vertex	parameters	channel
WWγ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW, Wγ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW, WZ
ZZγ	h_3^Z, h_4^Z	ZZ
Z$\gamma\gamma$	h_3^γ, h_4^γ	Zγ
ZγZ	f_{40}^Z, f_{50}^Z	Zγ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

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TGC: LEP scenario

In order to reduce the number of free TGC parameters, different scenarios can be used:

Equal couplings scenario: WWZ and $WW\gamma$ couplings are equal

LEP scenario: $\Delta\kappa_\gamma = (\cos^2\theta_W / \sin^2\theta_W)(\Delta g_1^Z - \Delta\kappa_Z)$ and $\lambda_Z = \lambda_\gamma$ (motivated by $SU(2) \times U(1)$ gauge invariance)

HISZ scenario $\Delta g^Z = \Delta\kappa_Z / (\cos^2\theta_w - \sin^2\theta_W)$,
$\Delta\kappa_\gamma = 2\Delta\kappa_Z \cos^2\theta_W / (\cos^2\theta_w - \sin^2\theta_W)$, and $\lambda_Z = \lambda_\gamma$

Number of free parameters:
2 for "equal couplings" and HISZ scenarios, 3 for LEP' scenario

$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

Event selection details

2 leptons	of opposite charge, $p_T > 25$ GeV
jet veto	for jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.5$
$E_{T,Rel}^{miss}$	$> 45{,}45{,}25$ GeV $(ee,\ e\mu,\ \mu\mu)$

Background estimates

top	data-driven (b-tagged)
W+jets	data-driven (fakes)
Drell-Yan	transfer-factor Drell-Yan control region

WZ - Details

Event selection

3 high-p_{T} isolated leptons, large $E_{\mathrm{T}}^{\mathrm{miss}}$

- Z candidate leptons: $|m_{\ell\ell} - m_Z| < 10\,\mathrm{GeV}$
- W lepton: tighter quality requirements
- $E_{\mathrm{T}}^{\mathrm{miss}} > 25\,\mathrm{GeV}$, $m_T^W > 20\,\mathrm{GeV}$

Fake estimate

Z+μ final state: sideband fit in jet-enriched CR

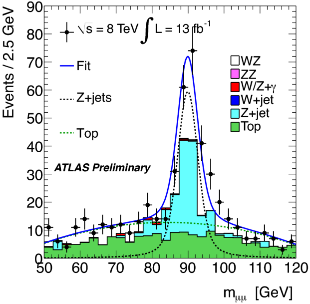
- flat top bg (Chebychev polynomial)
- peak: Z bg (Breit-Wigner $\oplus$ Crystal-Ball function)
- fit $\Rightarrow$ transfer factor $f = \frac{N_{SR}(MC)}{N_{CR}(MC)}$

Z+e final state: Matrix method: tight-cut and loose-cut samples

$$N_{fake}^{tight} = \frac{\epsilon_{fake}}{\epsilon_{real} - \epsilon_{fake}}(N^{loose}\epsilon_{real} - N^{tight})$$

Signal region

	events
ZZ	56.6±1.6
Z+jets/top	188±8±24
W/Z+γ	32±5
Bkg (total)	277±9±24
Signal expected	819±35
Total data	1094



ZZ details

- 4 isolated leptons, combined to same-flavor, opposite charge pairs

Electrons	isolated, $p_{\mathrm{T}} > 7\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.47$
Muons	isolated, $p_{\mathrm{T}} > 7\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$

first lepton $p_{\mathrm{T}} > 25\,\mathrm{GeV}$
combined to form same-flavor, oppositely-charged pairs $\rightarrow$ Z candidates
$66 < m_{\ell^+\ell^-} < 116\,\mathrm{GeV}$

Background estimate

Dominant background: $W^{\pm}/Z + X$ ($X = \gamma$ or jets - misidentified)

- Two control regions: *lljj* and *lllj* (inverted isolation requirements for *j*)
- Scale CR with measured fake factors

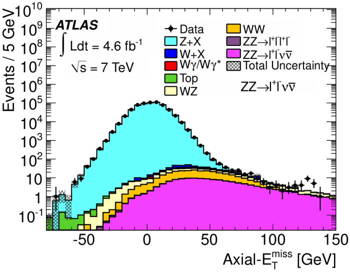
ZZ details II

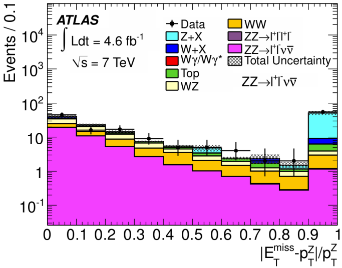
Event selection for ZZ in 2 lepton plus MET FS

exactly two leptons of same flavor with $76 < m_{ll} < 106\,\mathrm{GeV}$

to reduce WW $\rightarrow \ell\nu\ell\nu$: axial-$E_{\mathrm{T}}^{\mathrm{miss}} > 75\,\mathrm{GeV}$; $|E_{\mathrm{T}}^{\mathrm{miss}} - p_T^Z|/p_T^Z < 0.4$

to reduce WZ background: third lepton veto





after all selection cuts except the cut on the observable shown

Measured fiducial cross sections at 7 TeV

$\sigma^{fid}_{ZZ\rightarrow\ell^+\ell^-\ell^+\ell^-} = 25.4 \pm 3.3(stat) \pm 1.2(syst) \pm 1.0(lumi)$ fb

$\sigma^{fid}_{ZZ*\rightarrow\ell^+\ell^-\ell^+\ell^-} = 29.8 \pm 3.8(stat) \pm 1.7(syst) \pm 1.2(lumi)$ fb

$\sigma_{ZZ\rightarrow\ell^+\ell^-\nu\bar{\nu}} = 12.7 \pm 3.1(stat) \pm 1.7(syst) \pm 0.5(lumi)$ fb

Semileptonic WW/WZ Details

exactly 1 e/μ	isolated, $p_{\mathrm{T}} > 25\,\mathrm{GeV}$
missing E_{T}	$> 30\,\mathrm{GeV}$; $m_T > 40\,\mathrm{GeV}$
exactly 2 jets	$\|\eta\| < 2$ and $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ leading jet $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ $\Delta R(j_1, j_2) > 0.7$, $\Delta\eta(j_1, j_2) < 1.5$
$\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_1)$	> 0.8

Backgrounds

W/Z+jets	shape: MC, normalization: data driven
$t\bar{t}$, single top	MC
diboson, Wγ	MC
multijets	fully data driven

	e	μ
WW	1250 ± 60	1360 ± 70
WZ	276 ± 19	306 ± 21
W/Z+jets	$(89.5 \pm 14)\cdot 10^3$	$(94.2 \pm 15)\cdot 10^3$
top, Wγ, ZZ	$(42 \pm 3)\cdot 10^2$	$(43 \pm 3)\cdot 10^3$
multijet	$(50 \pm 15)\cdot 10^2$	$(39 \pm 123)\cdot 10^2$
total MC	$(100 \pm 14)\cdot 10^3$	$(103 \pm 15)\cdot 10^3$
total data	100055	103627

Wγ, Zγ

$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6,\mathrm{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

$W\gamma \to \ell\nu\gamma$

1 lepton $p_{\mathrm{T}} > 25\,\mathrm{GeV}$
photon $E_T^{\gamma} > 15\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}} > 35\,\mathrm{GeV}$
$m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 40\,\mathrm{GeV}$

$Z\gamma \to \ell^+\ell^-\gamma$

two opposite sign same-flavor leptons, $m_{ll} > 40\,\mathrm{GeV}$, isolated γ with $E_T^{\gamma} > 15\,\mathrm{GeV}$

$Z\gamma \to \nu\bar{\nu}\gamma$

$E_T^{\gamma} > 100\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}} > 90\,\mathrm{GeV}$
$\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma) > 2.6$
$\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, jet) > 0.4$

$\Delta R(\gamma, \ell) > 0.7$ to suppress FSR photons
Dominant background: W/Z + jets

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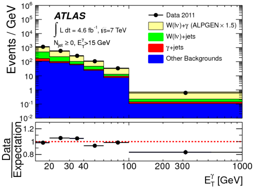
$W\gamma, Z\gamma$

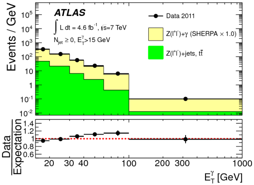
$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6\,\mathrm{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

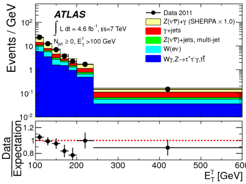
$W\gamma \to \ell\nu\gamma$



$Z\gamma \to \ell^+\ell^-\gamma$



$Z\gamma \to \nu\bar{\nu}\gamma$

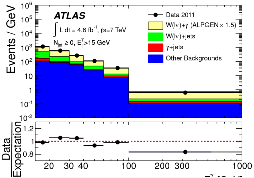


$W\gamma, Z\gamma$

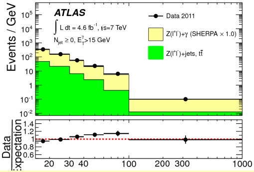
$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.6\,\text{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

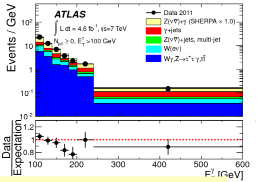
$W\gamma \to \ell\nu\gamma$



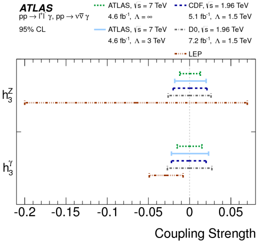
$Z\gamma \to \ell^+\ell^-\gamma$

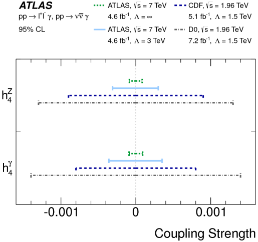


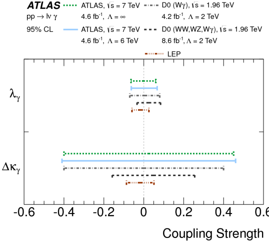
$Z\gamma \to \nu\bar{\nu}\gamma$



Limits on neutral and charged aTGCs:







Theory Models for VBS studies

3 different models were used:

Whizard

- Electroweak Chiral Lagrangian with non-linear EWSB and additional resonances with different masses, couplings (+ widths)

	weak isospin I	$I=0$	$I=1$	$I=2$
spin J	$J=0$	σ^0 (Higgs)		ϕ^0, $\phi^{\pm}$, $\phi^{\pm\pm}$ (Higgs triplet)
	$J=1$		ρ^0, $\rho^{\pm}$ (W',Z')	
	$J=2$	f^0 (KK-graviton)		t^0, $t^{\pm}$, $t^{\pm\pm}$

- Unitarization: k-matrix method

Pythia

- Electroweak chiral Lagrangian with anomalous quartic gauge couplings (which can be translated into resonances)
- Unitarization: Inverse-Amplitude method (Padé)

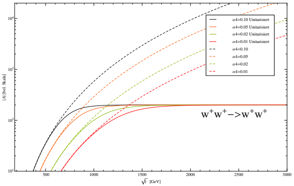
MadGraph

- Effective field theory with linear realization of the EWSB
- Unitarization: “Clipping”

Whizard's model for generic VBS resonances

Unitarity

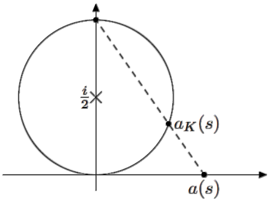
Absolute value of the physical amplitude W+W+ $\rightarrow$ W+W+ for different anomalous couplings with and without k-matrix unitarization



(M. Sekulla (Whizard graduate student) See also: arxiv/hep-ph:0806.4145v1.pdf

- Without a SM-Higgs, unitarity is violated in VBS
- Introduction of an additional resonance or anomalous coupling can lead to unitarity violation as well

- unitarization using K-MATRIX METHOD: projecting the amplitude on the Argand circle
- implemented in WHIZARD
- on a low-energy theorem amplitude (*), it acts as infinitely heavy resonance



(*) order-E^2-term in energy expansion

Argand circle

Current status: SM-Higgs terms are being included correctly in the unitarized amplitude (Whizard authors currently working on implementation)