

EWK Diboson production at ATLAS

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Standard Model Total Production Cross Section Measurements Status: Nov 2015



Motivation

- Diboson production cross-section measurements
 - important test of electroweak sector of Standard Model (SM) at TeV scale
 - Precision tests of theory
 - Important background for Higgs
 - Sensitivity to new physics, new heavy particles decaying to diboson
- Anomalous Triple Gauge Coupling (aTGC)
 - Vector boson self-couplings fundamental prediction of the Electroweak Sector of the SM
 - Probe to new physics through deviations of measured cross sections from predictions
- NB: mostly qq channel, gg contribution is below 10%

Cross-section measurement strategy

- "Cut and count" analysis of observed events
- Signal selection:
 - At least one boson decays to leptons to get better background suppression
 - Select high p_T leptons/jets, require high missing E_T (if v) + m_T cut for W
- Background estimation
 - Data-driven or simulation-only (in case of irreducible background)

$$\sigma_{tot}^{fid} = \frac{N_{data} - N_{backg.}}{A * BR * C * \int Ldt}$$
acceptance
$$A = \frac{N_{MC,gen}^{fid}}{N_{MC,gen}^{fid}} \text{ branching ratio} C = \frac{N_{Reco}^{Selected}}{N_{MC,gen}^{fid}}$$

- Uncertainties
 - Experimental: energy resolution/scale, reconstruction ID, luminosity ...
 - Theoretical: PDFs, parton shower, renormalization/factorization scale, ...

Anomalous couplings

- The non-abelian nature of the EWK sector of the SM predicts the selfinteraction of gauge bosons in the form of triple and quartic couplings
- General Lagrangian for WWZ or WW γ vertex that conserves C and P separately (V = Z or γ):

 $\mathcal{L}_{WWV} = -i g_{WWV} \Big[g_1^V (W_{\mu\nu}^{\dagger} W^{\mu} V^{\nu} - W_{\mu}^{\dagger} V_{\nu} W^{\mu\nu}) + \kappa_V W_{\mu}^{\dagger} W_{\nu} V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^{\dagger} W_{\nu}^{\mu} V^{\nu\lambda} \Big]$

- 5 parameters $\Delta g_1^Z = g_1^Z 1$, $\Delta \kappa_\gamma = \kappa_\gamma 1$, $\Delta \kappa_Z = \kappa_Z 1$, λ_γ , λ_Z - all should be 0 in SM
- LEP parametrization: $\Delta \kappa_Z = \Delta g_1^Z \Delta \kappa_\gamma tan^2 \theta_W$ and $\lambda_\gamma = \lambda_Z$ only 3 independent parameters left
- To set aTGC/aQGC limits
 - look for deviations in cross section measurements
 - look for enhancements in high p_T or high invariant mass regions

coupling	parameters	channel
$WW\gamma$	$\lambda_{\gamma}, \Delta k_{\gamma}$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	$f_{40}^{ar{Z}}, f_{50}^{ar{Z}}$	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Effective field theory

• Alternative description with Effective Field Theory (EFT)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

arXiv:1205.4231

 Λ - scale of new physics $O_i^{(d)}$ - new operators of higher dimensions

aTGC parameters can be converted to EFT couplings strengths,
 e.g. for d=6

$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2} \Delta g_1^Z \,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2} \Delta \kappa_\gamma - \frac{2}{m_Z^2} \Delta g_1^Z \,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2} \lambda \,, \end{aligned}$$

Recent RUN2 results

ZZ @ 13 TeV

- First diboson result at 13 TeV!
- 41 channel, 2 OS-SF $[e,\mu]$ pairs
- $p_T > 20 \text{ GeV}, 66 < m_{11} < 116 \text{ GeV}$
- 63 events in 3 channels

6

2

200

300

400

500

total exp. background: $0.62^{+1.08}_{-0.11}$

arXiv:1512.05314 accepted by PRL

ZZ: predictions still miss a full $O(\alpha_s^2)$ simulation

	Measurement	$\mathcal{O}(\alpha_{\rm s}^2)$ prediction
$\sigma_{ZZ \to e^+e^-e^+e^-}^{\text{fid}}$	$8.4 {}^{+2.4}_{-2.0}$ (stat.) ${}^{+0.4}_{-0.2}$ (syst.) ${}^{+0.5}_{-0.3}$ (lumi.) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma_{ZZ \to e^+ e^- \mu^+ \mu^-}^{\overline{\mathrm{fid}}}$	$14.7 {}^{+2.9}_{-2.5}$ (stat.) ${}^{+0.6}_{-0.4}$ (syst.) ${}^{+0.9}_{-0.6}$ (lumi.) fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\rm fid}_{ZZ\to\mu^+\mu^-\mu^+\mu^-}$	$6.8 {}^{+1.8}_{-1.5}$ (stat.) ${}^{+0.3}_{-0.3}$ (syst.) ${}^{+0.4}_{-0.3}$ (lumi.) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\rm fid}_{ZZ \to \ell^+ \ell^- \ell'^+ \ell'^-}$	$29.7 {}^{+3.9}_{-3.6}$ (stat.) ${}^{+1.0}_{-0.8}$ (syst.) ${}^{+1.7}_{-1.3}$ (lumi.) fb	$27.4^{+0.9}_{-0.8}$ fb
$\sigma_{ZZ}^{ m tot}$	$16.7 {}^{+2.2}_{-2.0}(\text{stat.}) {}^{+0.9}_{-0.7}(\text{syst.}) {}^{+1.0}_{-0.7}(\text{lumi.}) \text{ pb}$	$15.6^{+0.4}_{-0.4} \text{ pb}$

Recent RUN1 results

WZ Production

- Final state: : (W \rightarrow) $lv + (Z \rightarrow) ll$, l = e, mu
- Selection:
 - 3 isolated high p_T leptons, at least one lepton with $p_T > 25$ GeV, lepton from W with $p_T > 20$ GeV
 - $E_T^{miss} > 25 \text{ GeV}, M_T^W > 30 \text{ GeV}$
 - Z mass window: $|M_{ll} M_Z| < 10 \text{ GeV}$
- Data driven estimates for Z+jets, Zγ, WW and tt reducible backgrounds
 - fakes leptons from light flavor, heavy flavor jets and photons (for e)
- ZZ and other irreducible bkg from MC
 - latest theoretical calculations
 - mixture of NNLO and NLO (for $gg \rightarrow ZZ$)

Submitted to PRD

WZ Production cross-section

 $\sigma_{W^{\pm}Z \to \ell' \nu \ell \ell}^{\text{fid.}} = 35.2 \pm 0.9 \text{ (stat.)} \pm 0.8 \text{ (sys.)} \pm 0.8 \text{ (lumi.) fb},$ $\frac{\sigma_{W^{\pm}Z \to \ell' \nu \ell \ell}^{\text{fid.}}}{\sigma_{W^{-}Z \to \ell' \nu \ell \ell}^{\text{fid.}}} = 1.51 \pm 0.08 \text{ (stat.)} \pm 0.01 \text{ (sys.)} \pm 0.01 \text{ (lumi.)}$

 $\sigma_{W^{\pm}Z}^{\text{tot.}} = 24.3 \pm 0.6 \text{ (stat.)} \pm 0.6 \text{ (sys.)} \pm 0.4 \text{ (th.)} \pm 0.5 \text{ (lumi.)} \text{ pb}$

- Results are 20% higher than theory
 - Not covered by systematics
- Situation might improve with NNLO calculations
 - The only diboson channel for which we do not have NNLO predictions

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WZ Production - aTGC and aQGC

		aTGC			10	1		aQGC		-
$\Lambda_{ m co}$	Coupling	Expected	Obs	served	−ชິ	ATL	.AS		$\sqrt{s} = 8$ TeV, 20. K-matrix unitari pp $\rightarrow W^{\pm}Zjj$	3 fb ⁻¹ - zation -
2 TeV	Δg_1^Z $\Delta \kappa^Z$	[-0.023; 0.055] [-0.22: 0.36]	[-0.02	9 ; 0.050] 3 : 0.46]	0	.5				
	λ^Z	[-0.026; 0.026]	[-0.02	8;0.028]	_	0		X		
15 TeV	$\Delta g_1^Z \ \Delta \kappa^Z$	[-0.016; 0.033] [-0.17; 0.25]	[-0.01 [-0.1	9;0.029] 9;0.30]	-0	.5 obs. 95% exp. 95% ± 10 exp.	5 CL, W [±] Zjj 5 CL, W [±] Zjj ected		ł	
	λ^Z	[-0.016; 0.016]	[-0.01	7;0.017]	_	± 2σ exp exp. 95% Standard - 1	ected 5 CL, W [±] W [±] jj I Model 0 5		0.5	- - 1
	$\Delta g_1^Z \ \Delta \kappa^Z \ \lambda^Z$	[-0.016; 0.032] [-0.17; 0.25] [-0.016; 0.016]	[-0.019 [-0.19 [-0.010	9 ; 0.029] 9 ; 0.30] 6 ; 0.016]	_	-1	• Li	mits ext	racted fr	α ₄ om
EFT c	coupling	Expected [Te	eV ⁻²]	Obser	ved [ΓeV^{-2}]	• Ca	lculated	for alues of	
CW	V/Λ^2	[-3.7;7.	.6]	[4.3 ; 6	5.8]		toff scal	$e \Lambda_{co}$	
с _в с _{ww}	$_{W}/\Lambda^{2}$	[-270; 18] [-3.9; 3]	80] .8]	3—] [—]	320;2 3.9;2	210] 4.0]	$\alpha(\hat{s})$	$= \alpha(0)/$	$(1 + \hat{s}/2)$	$(\Lambda_{co}^2)^2$

$W^{\mp}W^{\pm}$ Production

- Final state: lvlv, l = e, mu in 0-jet bin
- Selection:
 - 2 opposite sign leptons
 - Z veto in same flavor channels:
 - $|M_{ll} M_Z| > 15 \text{ GeV}$
 - Large E_t^{miss} to further suppress Drell-Yan (~5% of total)
 - Hard Jet Veto to suppress top (~15%)
- Backgrounds
 - Top, Drell-Yan, W+jets, multijets data driven estimates
 - Diboson (WZ(γ *), ZZ, W/Z+γ) from MC

W⁺W[±] Production - cross-section

- Measurement is dominated by systematic uncertainties
 - Jet energy scale (4%)
 - Background uncertainty (3%)
 - Jet Veto requirement (3%)
- Measured cross section higher than SM prediction by ~1.5 σ
 - Situation improved with NNLO and NNLL corrections w.r.t. preliminary results from a year ago

Ratio of predictions to measurement

Final state	Total Cross section $pp \rightarrow WW$ [pb]
еµ	$70.5^{+1.3}_{-1.3}(\text{stat}) {}^{+5.8}_{-5.1}(\text{syst}) {}^{+2.1}_{-2.0}(\text{lumi})$
ee	$73.5^{+4.2}_{-4.1}(\text{stat}) {}^{+7.5}_{-6.4}(\text{syst}) {}^{+2.3}_{-2.1}(\text{lumi})$
$\mu\mu$	$73.9^{+3.0}_{-3.0}(\text{stat}) {}^{+7.1}_{-5.9}(\text{syst}) {}^{+2.2}_{-2.1}(\text{lumi})$
combined	$71.0^{+1.1}_{-1.1}$ (stat) $^{+5.7}_{-5.0}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
NNLO theory prediction	$63.2^{+1.6}_{-1.4}$ (scale)±1.2(PDF)

W⁺W[±] diff. X-section

- Various differential cross section predictions generally agree with data
 - All MCs are normalized to NNLO prediction for cross section
- All differences are accounted for in aTGC limits

$W^{\mp}W^{\pm}$ Production – aTGC

$\frac{\Delta = \infty}{\Delta k_{2}^{2}} = \frac{10.498,0.524}{[-0.053,0.059]} = \frac{10.215,0.267}{[-0.057,0.064]} = \frac{10.226,0.279}{[-0.028,0.045]}$ No constraints scenario λ^{Z} [-0.039,0.038] [-0.027,0.042] [-0.057,0.064] [-0.028,0.045] Δk^{Y} [-0.109,0.124] [-0.054,0.092] [-0.118,0.136] [-0.057,0.099] λ^{Y} [-0.081,0.082] [-0.051,0.052] [-0.088,0.089] [-0.055,0.055] LEP Δk^{Z} [-0.037,0.035] [-0.025,0.020] [-0.041,0.038] [-0.027,0.021] λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.033] [-0.020,0.020] HISZ Δk^{Z} [-0.026,0.030] [-0.012,0.022] [-0.028,0.033] [-0.020,0.020] HISZ Δk^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.034] [-0.020,0.020] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-7.62,7.38] [-4.61,4.60] EFT C_{WWW}/Λ^{2} [-7.62,7.38] [-4.61,4.60] EFT C_{WWW}/Λ^{2} [-12.58,14.32] [-5.87,10.54]	Scenario	Paramet	ter Expected	Observed	Expected	Observed
No constraints scenario $\lambda^{q_1^2}$ [-0.498,0.524] [-0.215,0.267] [-0.519,0.563] [-0.226,0.279] Δk^Z [-0.053,0.059] [-0.027,0.042] [-0.057,0.064] [-0.028,0.045] Δk^γ [-0.109,0.124] [-0.024,0.024] [-0.043,0.042] [-0.026,0.025] Δk^γ [-0.109,0.124] [-0.054,0.092] [-0.118,0.136] [-0.057,0.099] λ^γ [-0.081,0.082] [-0.051,0.052] [-0.088,0.089] [-0.055,0.055] LEP Δk^Z [-0.037,0.035] [-0.025,0.020] [-0.041,0.038] [-0.027,0.021] λ^Z [-0.031,0.031] [-0.019,0.019] [-0.033,0.033] [-0.020,0.020] HISZ Δk^Z [-0.026,0.030] [-0.012,0.022] [-0.028,0.033] [-0.020,0.020] Equal Couplings Δk^Z [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^Z [-7.62,7.38] [-4.61,4.60] EFT C_B/Λ^2 [-7.52,7.38] [-4.61,4.60] EFT C_B/Λ^2 [-35.8,38.4] [-20.9,26.3] C_W/Λ^2 [-12.58,14.32] [-5.87,10.54]			Λ =	= ∞	$\Lambda = \tilde{A}$	7 TeV
No constraints scenario λ^{Z} [-0.053,0.059] [-0.027,0.042] [-0.057,0.064] [-0.028,0.045] λ^{Z} [-0.039,0.038] [-0.024,0.024] [-0.043,0.042] [-0.026,0.025] Δk^{Y} [-0.109,0.124] [-0.054,0.092] [-0.118,0.136] [-0.057,0.099] λ^{Y} [-0.081,0.082] [-0.051,0.052] [-0.088,0.089] [-0.055,0.055] LEP Δk^{Z} [-0.037,0.035] [-0.025,0.020] [-0.041,0.038] [-0.027,0.021] λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.033] [-0.020,0.020] HISZ Δk^{Z} [-0.026,0.030] [-0.012,0.022] [-0.028,0.033] [-0.013,0.024] HISZ λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.034] [-0.020,0.020] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-7.62,7.38] [-4.61,4.60] EFT C_{WWW}/Λ^{2} [-7.62,7.38] [-4.61,4.60] EFT C_{WWW}/Λ^{2} [-12.58,14.32] [-5.87,10.54] • Limits extracted from p _T (leading lepton) distr. of eµ final state Many different scenarios considered by the second of the scenarios considered by the scenario considered by the s		Δg_1^Z	[-0.498,0.524]	[-0.215,0.267]	[-0.519,0.563]	[-0.226,0.279]
No constraints scenario λ^{Z} [-0.039,0.038] [-0.024,0.024] [-0.043,0.042] [-0.026,0.025] Δk^{γ} [-0.109,0.124] [-0.054,0.092] [-0.118,0.136] [-0.057,0.099] λ^{γ} [-0.081,0.082] [-0.051,0.052] [-0.088,0.089] [-0.055,0.055] LEP Δk^{Z} [-0.037,0.035] [-0.025,0.020] [-0.041,0.038] [-0.027,0.021] λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.033] [-0.020,0.020] HISZ Δk^{Z} [-0.026,0.030] [-0.012,0.022] [-0.028,0.033] [-0.013,0.024] HISZ λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.034] [-0.020,0.020] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] Equal Couplings Δk^{Z} [-7.62,7.38] [-4.61,4.60] EFT C_{WWW}/Λ^{2} [-7.62,7.38] [-4.61,4.60] C_{WWW}/Λ^{2} [-7.52,7.38] [-4.61,4.60] [-35.8,38.4] [-20.9,26.3] C_{W}/Λ^{2} [-12.58,14.32] [-5.87,10.54]		$\Delta k^{\hat{Z}}$	[-0.053,0.059]	[-0.027,0.042]	[-0.057,0.064]	[-0.028,0.045]
$\frac{\Delta k^{\gamma}}{V} = \begin{bmatrix} -0.109, 0.124 \\ [-0.054, 0.092] \\ [-0.118, 0.136] \\ [-0.057, 0.099] \\ [-0.055, 0.055] \\ [-0.081, 0.082] \\ [-0.051, 0.052] \\ [-0.088, 0.089] \\ [-0.055, 0.055] \\ [-0.055, 0.055] \\ [-0.035, 0.041] \\ [-0.017, 0.029] \\ [-0.017, 0.029] \\ [-0.033, 0.031] \\ [-0.019, 0.019] \\ [-0.033, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.028, 0.033] \\ [-0.020, 0.020] \\ [-0.020, 0.020] \\ [-0.021, 0.037] \\ [-0.020, 0.030] \\ [-0.020, 0.033] \\ [-0.020, 0.030] \\ [-0.024, 0.033] \\ [-0.020, 0.030] \\ [-0.024, 0.033] \\ [-0.020, 0.020] \\ [-0.034, 0.033] \\ [-0.020, 0.020] \\ [-0.024, 0.033] \\ [-0.020, 0.020] \\ [-0.024, 0.033] \\ [-0.020, 0.020] \\ [-0.024, 0.033] \\ [-0.020, 0.030] \\ [-0.024, 0.033] \\ [-0.020, 0.0$	No constraints s	scenario λ^Z	[-0.039,0.038]	[-0.024,0.024]	[-0.043,0.042]	[-0.026,0.025]
$\frac{\lambda^{\gamma}}{\log^2 1} \begin{bmatrix} -0.081,0.082 \\ [-0.051,0.052 \\ [-0.088,0.089 \\ [-0.055,0.055 \\ [-0.035,0.041 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.017,0.029 \\ [-0.033,0.033 \\ [-0.020,0.020 \\ [-0.012,0.022 \\ [-0.028,0.033 \\ [-0.020,0.020 \\ [-0.013,0.024 \\ [-0.020,0.020 \\ [-0.019,0.019 \\ [-0.033,0.034 \\ [-0.020,0.020 \\ [-0.017,0.024 \\ [-0.020,0.020 \\ [-0.013,0.024 \\ [-0.020,0.020 \\ [-0.019,0.019 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.019,0.019 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.019,0.019 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.017,0.021 \\ [-0.020,0.020 \\ [-0.017,0.024 \\ [-0.020,0.020 \\ [-0.013,0.034 \\ [-0.020,0.020 \\ [-0.013,0.034 \\ [-0.020,0.020 \\ [-0.013,0.034 \\ [-0.020,0.020 \\ [-0.013,0.034 \\ [-0.020,0.020 \\ [-0.014,0.048 \\ [-0.020,0.035 \\ [-0.041,0.048 \\ [-0.020,0.035 \\ [-0.041,0.048 \\ [-0.020,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.021,0.037 \\ [-0.020,0.020 \\ [-0.021,0.037 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.021,0.037 \\ [-0.021,0.037 \\ [-0.021,0.037 \\ [-0.020,0.020 \\ [-0.021,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.020 \\ [-0.034,0.033 \\ [-0.020,0.033 \\ [-0.020,0.033 \\ [-0.020,0.033 \\ [-0.020,0.033 \\ [-0.020,0.033 \\ [-0.020,0.03 \\ [-0.034,0.033 \\ [-0.020,0.033 \\ [-0.020,0.033 \\ [-0.020,0.03$		Δk^{γ}	[-0.109,0.124]	[-0.054,0.092]	[-0.118,0.136]	[-0.057,0.099]
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		λ^{γ}	[-0.081,0.082]	[-0.051,0.052]	[-0.088,0.089]	[-0.055,0.055]
LEP Δk^{Z} [-0.037,0.035] [-0.025,0.020] [-0.041,0.038] [-0.027,0.021] λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.033] [-0.020,0.020] HISZ Δk^{Z} [-0.026,0.030] [-0.012,0.022] [-0.028,0.033] [-0.013,0.024] λ^{Z} [-0.031,0.031] [-0.019,0.019] [-0.033,0.034] [-0.020,0.020] Equal Couplings Δk^{Z} [-0.041,0.048] [-0.020,0.035] [-0.045,0.052] [-0.021,0.037] λ^{Z} [-0.030,0.030] [-0.019,0.019] [-0.034,0.033] [-0.020,0.020] Equal Couplings λ^{Z} [-7.62,7.38] [-4.61,4.60] C_{WWW}/Λ^{2} [-7.62,7.38] [-4.61,4.60] EFT C_{B}/Λ^{2} [-35.8,38.4] [-20.9,26.3] C_{W}/Λ^{2} [-12.58,14.32] [-5.87,10.54] C_{Q}/Λ^{2} [-12.58,14.32] [-5.87,10.54]		Δg_1^Z	[-0.033,0.037]	[-0.016,0.027]	[-0.035,0.041]	[-0.017,0.029]
$\frac{\lambda^{Z}}{\mu_{1}} = \begin{bmatrix} -0.031, 0.031 \\ -0.019, 0.019 \\ -0.033, 0.033 \\ -0.020, 0.020 \\ \hline \\ HISZ \\ \lambda^{Z} \\ \hline \\ \hline \\ \hline \\ \hline \\ Equal Couplings \\ \lambda^{Z} \\ \hline \\ \hline \\ \hline \\ Cup WW/\Lambda^{2} \\ \hline \\ \\ \hline \\ \\ EFT \\ \hline \\ \\ C_{W}/\Lambda^{2} \\ \hline \\ \\ \hline \\ \\ C_{W}/\Lambda^{2} \\ \hline \\ \hline \\ \\ \hline \\ \\ \hline \\ \\ C_{W}/\Lambda^{2} \\ \hline \\ \hline \\ \hline \\ \hline \\ \\ \hline \\ \hline \\ \hline \\ \hline \\ \\ \hline \\ $	LEP	$\Delta k^{\hat{Z}}$	[-0.037,0.035]	[-0.025,0.020]	[-0.041,0.038]	[-0.027,0.021]
HISZ Δk^Z [-0.026,0.030][-0.012,0.022][-0.028,0.033][-0.013,0.024] λ^Z [-0.031,0.031][-0.019,0.019][-0.033,0.034][-0.020,0.020]Equal Couplings Δk^Z [-0.041,0.048][-0.020,0.035][-0.045,0.052][-0.021,0.037] λ^Z [-0.030,0.030][-0.019,0.019][-0.034,0.033][-0.020,0.020]ScenarioParameterExpectedObserved[-0.034,0.033][-0.020,0.020] C_{WWW}/Λ^2 [-7.62,7.38][-4.61,4.60]•Limits extracted from C_B/Λ^2 [-35.8,38.4][-20.9,26.3]•Limits extracted from C_W/Λ^2 [-12.58,14.32][-5.87,10.54]•Many differentscenariosconsideredScenariosconsidered		λ^Z	[-0.031,0.031]	[-0.019,0.019]	[-0.033,0.033]	[-0.020,0.020]
H132 λ^{Z} [-0.031,0.031][-0.019,0.019][-0.033,0.034][-0.020,0.020]Equal Couplings Δk^{Z} [-0.041,0.048][-0.020,0.035][-0.045,0.052][-0.021,0.037] λ^{Z} [-0.030,0.030][-0.019,0.019][-0.034,0.033][-0.020,0.020]ScenarioParameterExpectedObserved[-0.034,0.033][-0.020,0.020] C_{WWW}/Λ^{2} [-7.62,7.38][-4.61,4.60][-0.034,0.033][-0.020,0.020]EFT C_{B}/Λ^{2} [-35.8,38.4][-20.9,26.3][-4.61,4.60]distr. of eµ final state C_{W}/Λ^{2} [-12.58,14.32][-5.87,10.54]Many different	UIS7	Δk^Z	[-0.026,0.030]	[-0.012,0.022]	[-0.028,0.033]	[-0.013,0.024]
Equal Couplings Δk^Z λ^Z [-0.041,0.048] [-0.030,0.030][-0.020,0.035] [-0.019,0.019][-0.045,0.052] [-0.034,0.033][-0.021,0.037] [-0.020,0.020]ScenarioParameterExpectedObserved [-0.02,7.38][-0.034,0.033][-0.020,0.020]EFT C_{WWW}/Λ^2 C_B/Λ^2 C_W/Λ^2 [-7.62,7.38] [-35.8,38.4][-4.61,4.60] [-20.9,26.3]•Limits extracted from p_T (leading lepton) distr. of eµ final stateEFT C_B/Λ^2 C_W/Λ^2 [-12.58,14.32][-5.87,10.54]•Limits extracted from p_T (leading lepton) distr. of eµ final state	пы	λ^Z	[-0.031,0.031]	[-0.019,0.019]	[-0.033,0.034]	[-0.020,0.020]
Equar Couplings λ^Z [-0.030,0.030][-0.019,0.019][-0.034,0.033][-0.020,0.020]ScenarioParameterExpectedObservedObserved Γ_T (leading lepton)EFT C_W/Λ^2 [-7.62,7.38][-4.61,4.60]distr. of eµ final state C_W/Λ^2 [-35.8,38.4][-20.9,26.3]distr. of eµ final state C_W/Λ^2 [-12.58,14.32][-5.87,10.54]Many different	Equal Coupling	Δk^Z	[-0.041,0.048]	[-0.020,0.035]	[-0.045,0.052]	[-0.021,0.037]
ScenarioParameterExpectedObserved C_{WWW}/Λ^2 $[-7.62,7.38]$ $[-4.61,4.60]$ p_T (leading lepton)EFT C_B/Λ^2 $[-35.8,38.4]$ $[-20.9,26.3]$ distr. of eµ final state C_W/Λ^2 $[-12.58,14.32]$ $[-5.87,10.54]$ • Many different	Equal Coupling	λ^{Z}	[-0.030,0.030]	[-0.019,0.019]	[-0.034,0.033]	[-0.020,0.020]
ScenarioParameterExpectedObserved C_{WWW}/Λ^2 [-7.62,7.38][-4.61,4.60]EFT C_B/Λ^2 [-35.8,38.4][-20.9,26.3] C_W/Λ^2 [-12.58,14.32][-5.87,10.54]Centric extracted from					— I imita	extracted from
EFT C_{WWW}/Λ^2 [-7.62,7.38] [-4.61,4.60] C_B/Λ^2 [-35.8,38.4] [-20.9,26.3] C_W/Λ^2 [-12.58,14.32] [-5.87,10.54] - Many different scenarios considered (Scenario	Parameter	Expected	Observed		ding leaden)
EFT C_B/Λ^2 [-35.8,38.4] [-20.9,26.3] C_W/Λ^2 [-12.58,14.32] [-5.87,10.54] • Many different scenarios considered [C_{WWW}/Λ^2	[-7.62,7.38]	[-4.61,4.60	p_{T} (let	ang lepton)
C_W/Λ^2 [-12.58,14.32] [-5.87,10.54] • Many different	EFT	C_B/Λ^2	[-35.8,38.4]	[-20.9,26.3] aistr. (different
		C_W/Λ^2	[-12.58,14.32]	[-5.87,10.54	4] • Iviany	interent

aTGC limits summary

- Limits at 8 TeV are 1.5-2.5 times better than at 7 TeV
- Measurements of WW and WZ diboson production provide complementary results
- Combined together give the most stringent limits on WWZ couplings

Other RUN1 results

JHEP 1501 (2015) 049

WW/WZ Semileptonic Production (7TeV)

- Final state: $(W \rightarrow) lv (W/Z \rightarrow) jj, l = e, mu$ Backgrounds:
- Selection:
 - Exactly one lepton
 - Two jets with $|\Delta R|>0.7$ if $p_T(jj)<250$ GeV, $|\Delta\eta|<1.5,$ and $25< m_{jj}<250$ GeV
 - $E_T^{\text{miss}} > 30 \text{ GeV}, m_T^{W} > 40 \text{ GeV},$

• W+jets (~85%),Z+jets (~4%), Multijet (~4%), Top (~5%)

JHEP 1404 (2014) 031

Vector Boson Fusion Production of Zjj

- Final state: $(Z \rightarrow) l^+l^- jj$
- Signature:
 - Two leptons with m(ll) consistent with m_Z
 - Two high p_T jets
 - Search region:
 - $p_{T}(ll) > 20 \text{ GeV}$
 - $m_{jj} > 250 \text{ GeV}, p_T^{\text{balance}} < 0.15$
 - No jets in rapidity gap between the two high p_T jets
- Fiducial cross sections measured in several regions, including a search region with $m_{jj} > 1$ TeV to obtain high sensitivity to EW production of Zjj (35% of events)
 - Reject background only hypothesis at $> 5\sigma$

 $\sigma_{\rm EW} (m_{jj} > 1 \,{\rm TeV}) = 10.7 \pm 0.9 \,({\rm stat}) \pm 1.9 \,({\rm syst}) \pm 0.3 \,({\rm lumi}) \,{\rm fb},$ theoretical prediction $9.38 \pm 0.05 \,({\rm stat}) \,{}^{+0.15}_{-0.24} \,({\rm scale}) \pm 0.24 \,({\rm PDF}) \pm 0.09 \,({\rm model}) \,{\rm fb}.$

aTGC	$\Lambda = 6 \text{ TeV} (\text{obs})$	$\Lambda=6~{\rm TeV}~({\rm exp})$	$\Lambda = \infty \text{ (obs)}$	$\Lambda = \infty \ (\exp)$
$\Delta g_{1,Z}$	[-0.65, 0.33]	[-0.58, 0.27]	[-0.50, 0.26]	[-0.45, 0.22]
λ_Z	[-0.22, 0.19]	[-0.19, 0.16]	[-0.15, 0.13]	[-0.14, 0.11]

3000

m_{ii} [GeV]

Phys.Rev.Lett. 113 (2014) 141803

Vector boson scattering: W±W±jj

First evidence of VBS WWjj at LHC ! Final state: $l^{\pm}v l^{\pm}v jj$ **Fiducial Cross section** Selection 1.52 ± 0.11 fb Strong and SM prediction • Two high p_T leptons, ≥ 2 jets Electroveak Observed $2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})$ fb W±W±ii • m(ll) > 20 GeVSignificance observed: 4.5σ expected: 3.4σ $|m(ee) - m_Z| > 10 \text{ GeV}$ 0.95 ± 0.06 fb Electroveak SM prediction • $E_{T}^{miss} > 40 \text{ GeV}$ W±W±ii Observed $1.3 \pm 0.4(stat) \pm 0.2(syst)$ fb VBS region b-jet veto Significance observed: 3.6o expected: 2.8σ Inclusive: m(jj) > 500 GeVVBS: $|\Delta y_{ii}| > 2.4$ ATLAS EW VBS non-VBS 0.6 20.3 fb⁻¹, Vs = 8 TeV $pp \rightarrow W^{\pm}W^{\pm}jj$ Events 30F ATLAS 0.4K-matrix unitarization Data 2012 20.3 fb⁻¹, vs = 8 TeV XXX Syst. Uncertainty W[±]W[±]jj Electroweak m.; > 500 GeV W[±]W[±]ii Strong Prompt 20 Conversions -0.2 confidence intervals Other non-prompt 15 68% CL **VBS** Region 95% CL expected 95% CL 10 Standard Model -0.4 -0.3 -0.2 -0.1 0.1 0.2 0.3 0.4 Measured fiducial cross section in 2 6 8 9 3 5 ∆y_"| VBS region used to set limits on aQGC's

Phys. Rev. Lett. 115, 031802 (2015)

Wyy Production

- Final state $(W \rightarrow) l \nu \gamma \gamma$
- Selection:
 - Lepton/photon $p_T > 20 \text{ GeV}$
 - $E_T^{miss} > 25 \text{ GeV}$
 - $m_T > 40 \text{ GeV}$
 - Restrictions on eγγ system to reduce electron mis-id. (mainly from Zγ)
- Backgrounds:
 - Data driven estimates for photon fakes (Wγj+Wjj) and lepton fakes (γγ+jets)

First evidence of triboson production !

Fiducial Cross section

Big data/MCFM discrepancy in inclusive Maybe NNLO will be closer to data ?

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

Exclusive cross section measurement with $m(\gamma\gamma) > 300$ GeV used to extract aQGC limits with different exponents in form factor

Conclusions

- Fiducial, total and differential cross-section measurements for diboson processes at ATLAS allow precision comparisons to state-of-the-art theory predictions
- In some cases have reached sensitivity to NNLO corrections!
- 8 TeV LHC data for the first time gives us evidence for vector boson scattering
- Also seeing evidence for tri-boson production!
- RUN1 data allow to set competitive limits on aTGCs and aQGCs
- Measurements with different final states give complementary results
- Measurements at 8 TeV are almost finished
- Analysis of 13 TeV data has been started, first results already available, a lot of new interesting results expected

Summary of Diboson measurements in RUN1 (recent results missing)

Multiboson Cross S	Section Measurements	Status: Nov 2015	∫£ dt _ [fb ⁻¹]	Reference
$\sigma^{\rm fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$	σ = 44.0 + 3.2 - 4.2 pb (data) 2yNNLO (theory)	ATLAS Preliminary	4.9	JHEP 01, 086 (2013)
$\sigma^{\rm fid}(W\gamma \to \ell \nu \gamma)$	σ = 2.77 ± 0.03 ± 0.36 pb (data) NNLO (theory)		4.6	PRD 87, 112003 (2013)
$-[n_{jet}=0]$	σ = 1.76 ± 0.03 ± 0.22 pb (data) NNLO (theory)	Run 1 $\sqrt{s} = 7, 8 \text{ TeV}$	4.6	PRD 87, 112003 (2013)
$\sigma^{\rm fid}(Z\gamma \to \ell\ell\gamma)$	$\sigma = 1.31 \pm 0.02 \pm 0.12 \text{ pb} \text{ (data)} $ NNLO (theory)		4.6	PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
$-[n_{jet}=0]$	σ = 1.05 ± 0.02 ± 0.11 pb (data) NNLO (theory)		4.6	PRD 87, 112003 (2013)
$\sigma^{\rm fid}(W\gamma\gamma \to \ell v\gamma\gamma)$	$\sigma = 6.1 + 1.1 - 1.0 \pm 1.2 ~\rm{fb}~(data) \\ \rm{MCFM}~\rm{NLO}~(theory) \label{eq:stars}$	A	20.3	arXiv:1503.03243 [hep-ex]
$-[n_{jet}=0]$	$\sigma = 2.9 + 0.8 - 0.7 + 1.0 - 0.9 \text{ fb (data)} \\ \text{MCFM NLO (theory)}$	▲	20.3	arXiv:1503.03243 [hep-ex]
$\sigma^{\rm fid}(pp \rightarrow WV \rightarrow \ell \nu qq)$	$\sigma = 1.37 \pm 0.14 \pm 0.37 \text{ pb} \text{ (data)} \\ \text{MC@NLO (theory)} \bullet$		4.6	JHEP 01, 049 (2015)
$\sigma^{ m fid}({\sf W}^{\pm}{\sf W}^{\pm}{\sf jj})$ EWK	$\sigma = 1.3 \pm 0.4 \pm 0.2 \text{ fb} \text{ (data)} \\ \text{PowhegBox (theory)} $	A	20.3	PRL 113, 141803 (2014)
$\sigma^{\text{total}}(pp \rightarrow WW)$	$\sigma = 51.9 \pm 2.0 \pm 4.4 \text{ pb} (data)$ $\sigma = 71.4 \pm 1.2 \pm 5.5 - 4.9 \text{ pb} (data)$ $MCFM (theory)$		4.6 20.3	PRD 87, 112001 (2013) ATLAS-CONF-2014-033
−σ ^{fid} (WW→ee) [n _{jet} =0]	$\sigma = 56.4 \pm 6.8 \pm 10.0 \text{ (b} (data) \\ \text{MCFM (theory)} \qquad \qquad \bullet$	Theory	4.6	PRD 87, 112001 (2013)
$-\sigma^{\text{fid}}(WW \rightarrow \mu\mu) [n_{\text{jet}}=0]$	$\sigma = 73.9 \pm 5.9 \pm 7.5 \text{ fb (data)} \\ \text{MCFM (theory)} $	LHC pp \sqrt{s} = 7 TeV	4.6	PRD 87, 112001 (2013)
$-\sigma^{fid}(WW \rightarrow e\mu) [n_{jet}=0]$	$\sigma = 262.3 \pm 12.3 \pm 23.1 \text{ (b) (data)}$	Data stat	4.6	PRD 87, 112001 (2013)
− σ ^{fid} (WW→eμ) [n _{jet} ≥0]	σ = 563.0 ± 28.0 + 79.0 − 85.0 fb (data) MCFM (theory)	stat+syst	4.6	arXiv:1407.0573 [hep-ex]
$\sigma^{\text{total}}(pp \rightarrow WZ)$	$\sigma = 19.0 + 1.4 - 1.3 \pm 1.0 \text{ pb} \text{ (data)}$ $\sigma = 20.3 + 0.8 - 0.7 + 1.4 - 1.3 \text{ pb} \text{ (data)}$	LHC pp $\sqrt{s} = 8$ TeV	4.6	EPJC 72, 2173 (2012) ATLAS-CONF-2013-021
$-\sigma^{\text{fid}}(WZ \rightarrow \ell \nu \ell \ell)$	$\sigma = 99.2 + 3.8 - 3.0 + 6.0 - 6.2 \text{ fb (data)}$	▲ Stat stat+syst	13.0	ATLAS-CONF-2013-021
$\sigma^{\text{total}}(\mathbf{pp} \rightarrow ZZ) \\ -\sigma^{\text{total}}(\mathbf{pp} \rightarrow ZZ \rightarrow 4\ell) \\ -\text{fid}(ZZ \rightarrow 4\ell)$	$ \sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \text{ pb (data)} $ $ \sigma = 7.1 + 0.5 - 0.4 = 0.4 \text{ pb (data)} $ $ \sigma = 7.6.1 \pm 0.5.0 \pm 4.0 \text{ ty (data)} $ $ \sigma = 7.6.0 \pm 10.0 \pm 4.0 \text{ ty (data)} $ $ \sigma = 107.0 \pm 9.0 \pm 5.0 \text{ tb (data)} $ $ \sigma = 25.4 \pm 3.3 - 3.0 \pm 1.0 - 7.2 \text{ (fieldata)} $		4.6 20.3 4.5 20.3 4.6	JHEP 03, 128 (2013) ATLAS-CONF-2013-020 arXiv:1403.5657 [hep-ex] arXiv:1403.5657 [hep-ex] JHEP 03, 128 (2013)
$-\partial^{\text{fid}}(\mathbf{Z}\mathbf{Z} \to 4t)$	$\sigma = 20.7 + 1.3 - 1.2 \pm 1.0$ (b) (data) MCFM (theory) $\sigma = 29.8 + 3.8 - 3.5 + 2.1 - 1.9$ (b) (data)		20.3	ATLAS-CONF-2013-020
$-\sigma^{\mathrm{ind}}(\mathbb{Z}\mathbb{Z}^* \to 4\ell)$	PowhegBox & gg2ZZ (theory) σ		4.6	JHEP 03, 128 (2013)
$-\sigma^{\mathrm{nu}}(\mathbf{Z}\mathbf{Z}^* \rightarrow \ell\ell\nu\nu)$	PowhegBox & gg2ZZ (the)		4.6	JHEP 03, 128 (2013)
	0.2 0.4 0.6 0.8 1.0 1.2	1.4 1.6 1.8 2.0 2.2 2.4 2.6		
		data/theory	1	

Summary of charged aTGC limits (recent results missing)

• No deviation from SM observed

Charged aTGC WW γ

Charged aTGC WWZ

September 20	015	CMS	<u> </u>					ptember 2	2015	CMS ATLAS					
	Central Fit Value	D0		Channel	Limits	[/ dt	<u>v</u> e		Fit Value	D0 LEP		Channel	Limits	∫∠dt	√s
		LLF	1 • 1	M/M		10.0.1	7 7-1/	$\Delta \kappa_{7}$				ww	[-4.3e-02, 4.3e-02]	4.6 fb ⁻¹	7 TeV
$\Delta \kappa_{\gamma}$				ννγ	[-4.10-01, 4.60-01]	4.6 fD	7 Tev	2	- F			ww	[-6.0e-02, 4.6e-02]	19.4 fb ⁻¹	8 TeV
				Wγ	[-3.8e-01, 2.9e-01]	5.0 fb ⁻¹	7 TeV					WV	[-9.0e-02, 1.0e-01]	4.6 fb ⁻¹	7 TeV
				WW	[-2.1e-01, 2.2e-01]	4.9 fb ⁻¹	7 TeV			H		WV	[-4.3e-02, 3.3e-02]	5.0 fb ⁻¹	7 TeV
		- - •		ww	[-1.3e-01, 9.5e-02]	19.4 fb ⁻¹	8 TeV			•		LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb ⁻¹	0.20 TeV
				WV	[-2.1e-01, 2.2e-01]	4.6 fb ⁻¹	7 TeV	λ _z	H			ww	[-6.2e-02, 5.9e-02]	4.6 fb ⁻¹	7 TeV
				W/V	[-1 1e-01 1 4e-01]	5.0 fb ⁻¹	7 ToV					ww	[-4.8e-02, 4.8e-02]	4.9 fb ⁻¹	7 TeV
			· ·	***		5.0 10	1100				→	ww	[-2.4e-02, 2.4e-02]	19.4 fb ⁻¹	8 TeV
			• • •	D0 Comb.	[-1.66-01, 2.56-01]	8.6 fb ⁻	1.96 TeV			H		WZ	[-4.6e-02, 4.7e-02]	4.6 fb ⁻¹	7 TeV
		H		LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb ⁻¹	0.20 TeV					WV	[-3.9e-02, 4.0e-02]	4.6 fb ⁻¹	7 TeV
λ.				Wγ	[-6.5e-02, 6.1e-02]	4.6 fb ⁻¹	7 TeV					WV	[-3.8e-02, 3.0e-02]	5.0 fb	7 TeV
.4		⊢		Wγ	[-5.0e-02, 3.7e-02]	5.0 fb ⁻¹	7 TeV					D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb ⁻¹	1.96 TeV
				WW	[-4.8e-02, 4.8e-02]	4.9 fb ⁻¹	7 TeV		•			LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb ⁻¹	0.20 TeV
				14/14/	[-2.40.02, 2.40.02]	10.4.6-1	9 ToV	Δg_1^Z				VV VV	[-3.9e-02, 5.2e-02]	4.6 fb	7 TeV
			-1	****	[-2.48-02, 2.48-02]	19.4 10						VV VV	[-9.50-02, 9.50-02]	4.9 ID	7 TeV
		-		WV	[-3.9e-02, 4.0e-02]	4.6 fb ⁻	7 IeV				_	VV VV	[-4.7e-02, 2.2e-02]	19.4 ID	
		H	-	WV	[-3.8e-02, 3.0e-02]	5.0 fb ⁻¹	7 TeV					VVZ	[-5.7e-02, 3.5e-02] [-5.5e-02, 7.1e-02]	4.0 ID	7 TeV
		H	•	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb ⁻¹	1.96 TeV			·		NV V	[-3.4e-02, 8.4e-02]	4.0 ID 8.6 fb ⁻¹	1 96 TeV
		H	- i , , , ,	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb ⁻¹	0.20 TeV	I		, ,		LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb ⁻¹	0.20 TeV
-(0.5		D	0.5	1	1.5					0	C	.2		0.4
					aTGC Lim	its @95	5% C.L.						aTGC Limi	ts @95	% C.L.

Summary of neutral aTGC limits (recent results missing)

• No deviation from SM observed

Neutral aTGC ZyZ, ZZZ

Neutral aTGC ZZ γ , Z $\gamma \gamma$

Mar 2015				Feb 2015			
			ATLAS Limits CMS Prel. Limits				ATLAS Limits — CMS Prel. Limits — CDF Limit —
٤Ŷ	HH	ZZ	-0.015 - 0.015 4.6 fb ⁻¹	. 2		Zγ	-0.015 - 0.016 4.6 fb ⁻¹
4	—	ZZ	-0.005 - 0.005 19.6 fb ⁻¹	h'a		-1	
	\mapsto	ZZ (2l2v)	-0.004 - 0.003 24.7 fb ⁻¹	5	H	27	-0.003 - 0.003 5.0 fb
	H	ZZ (comb)	-0.003 - 0.003 24.7 fb ⁻¹		H	Ζγ	-0.005 - 0.005 19.5 fb ⁻
.7	H	77	-0.013 - 0.013 4 6 fb ⁻¹		HH	Zγ	-0.022 - 0.020 5.1 fb ⁻¹
$ t_4$	H	 ZZ	-0.004 - 0.004 19.6 fb ⁻¹	ьZ	H	Zγ	-0.013 - 0.014 4.6 fb ⁻¹
	H	ZZ (2l2v)	-0.003 - 0.003 24.7 fb ⁻¹	n_3^-	H	Zγ	-0.003 - 0.003 5.0 fb ⁻¹
	н	ZZ (comb)	-0.002 - 0.003 24.7 fb ⁻¹		—	Zγ	-0.004 - 0.004 19.5 fb ⁻¹
ĘŶ	⊢I	ZZ	-0.016 - 0.015 4.6 fb ⁻¹		H	Zγ	-0.020 - 0.021 5.1 fb ⁻¹
5	—	ZZ	-0.005 - 0.005 19.6 fb ⁻¹	· ^γ · · · ·	i	Ζγ	-0.009 - 0.009 4 6 fb ⁻¹
	\mapsto	ZZ(2l2v)	-0.003 - 0.004 24.7 fb ⁻¹	h, x100		-1 72	-0.001 - 0.001 = 0.001
	н	ZZ(comb)	-0.003 - 0.003 24.7 fb ⁻¹	4		2 / 7	
<i>i</i> 7	H	ZZ	-0.013 - 0.013 4.6 fb ⁻¹		H	Ζγ	-0.004 - 0.004 19.5 fb ⁻¹
I ₅	⊢i	ZZ	-0.004 - 0.004 19.6 fb ⁻¹	h^{Z} v100		Ζγ	-0.009 - 0.009 4.6 fb ⁻¹
	\mapsto	ZZ (2l2v)	-0.003 - 0.003 24.7 fb ⁻¹	11 ₄ ×100	н	Zγ	-0.001 - 0.001 5.0 fb ⁻¹
	H	ZZ (comb)	-0.002 - 0.002 24.7 fb ⁻¹		\vdash	Zγ	-0.003 - 0.003 19.5 fb ⁻¹
-0.5	0	0.5	1 1.5 $\times 10^{-1}$	-0.5	0	0.5	1 1.5 $\times 10^{-1}$
		aTG	C Limits @95% C.L.				aTGC Limits @95% C.L.

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• Exclusive: $N_{jet} = 0$, Inclusive: $N_{jet} \ge 0$

Jet multiplicity

W_{γ} / Z_{γ} Production - NNLO calculations

- NNLO calculation (arXiv:1407.1618)
 - Large radiative corrections for Wγ
 - 19% correction for Wγ
 - 6% increase for Zγ
- Agreement with data is improved
- Fiducial cross section with NLO and NNLO calculations below

Process	NLO (fb)	NNLO (fb)	Measurement (fb)
Wγ	2065.2 ± 0.9	2456 ± 6	$2770 \pm 30(stat) \pm 330(syst) \pm 140(lumi)$
Ζγ	1226.2 ± 0.4	1305 ± 3	$1310 \pm 20(stat) \pm 110(syst) \pm 50(lumi)$

W_{γ} / Z_{γ} Production - aTGC

• Limits on anomalous couplings from fiducial measurement with $E_T^{\gamma} > 100 \text{ GeV}$

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WW/WZ Semileptonic (7TeV) - aTGC

 p_T(jj) used to extract limits on parameters in anomalous couplings framework and Effective Field Theory

EFT limits have been calculated (first at LHC!)

Parameter	Observed Limit
c_{WWW}/Λ^2	$[-9.5, 9.6] \text{ TeV}^{-2}$
c_B/Λ^2	$[-64, 69] \text{ TeV}^{-2}$
c_W/Λ^2	$[-13, 18] \text{ TeV}^{-2}$

8 TeV WW/WZ paper in preparation

W⁺W[±] Production (older result)

• Previois results (NLO only) bigger disagreement with data

