Diboson Physics at ATLAS

Konstantinos Bachas
on behalf of the ATLAS Collaboration

Aristotle University of Thessaloniki

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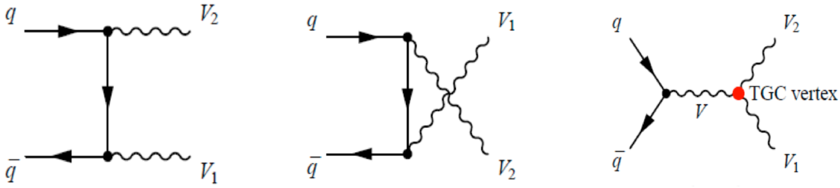
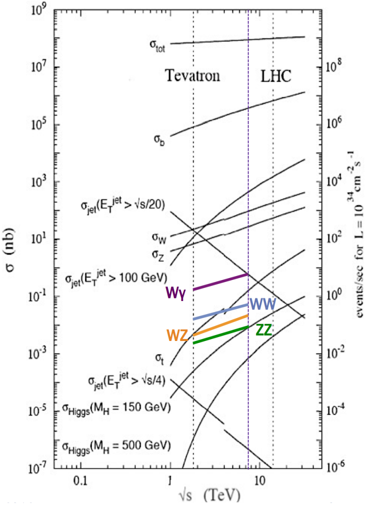
Diboson physics overview

- Diboson production cross-section measurements
  - High energy test of Standard Model(SM) predictions at TeV scale
  - Irreducible background to Higgs
  - Sensitivity to new particles decaying to diboson (Technicolor, SUSY)
- Anomalous Triple Gauge Couplings (aTGC)
  - Vector boson self-couplings fundamental prediction of the Electroweak Sector of SM
  - Probe to new physics through deviations of measured cross sections from predictions



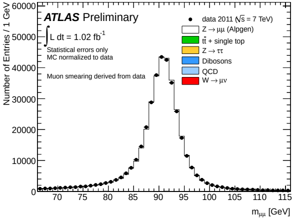
Diboson measurements with ATLAS at the LHC

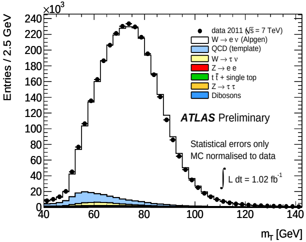
- Diboson measurements performed at ATLAS with 2011 data @ 7TeV:
  - WW, WZ, ZZ, W/Zγ
  - Using the full dataset available ($\sim 4.7 fb^{-1}$)
- Diboson measurements performed at ATLAS with 2012 data@ 8TeV:
  - ZZ with $5.8 fb^{-1}$
- Leptonic decay channels with clean signals and low background
- Small cross sections O(1-100pb)



Common signatures and selections

- Leptons
  - High-p_T leptons $> 7 - 20 GeV$ in geometrical acceptance of $|\eta| < 2.7(\mu)$, $< 2.47(e)$
  - Calorimeter and track isolation utilised
  - Single lepton triggers
- Photons
  - $p_T > 15 GeV$ in geometrical acceptance of $|\eta| < 2.4$
  - Calorimeter based isolation
- $Z \to l^+ l^-$ selection
  - Invariant mass in windows of 10 to 25 GeV away from PDG mass
- $W \to l\nu$ selection
  - Large Missing transverse energy, E_T^{miss} cuts starting $> 25 GeV$
    - Computed from jets, leptons and calorimetric clusters
    - $|\eta|_{E_T^{miss}} < 4.5$
  - Transverse mass, m_T, cuts starting $> 20 GeV$

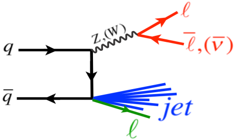


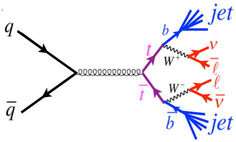


Common backgrounds

- Mainly 3 sources of background common to diboson processes

- W/Z+jets
  - Genuine isolated high-p_T leptons from boson decay
  - Lepton(s) from heavy and light flavour decays
  - Lepton-like jets
- $t\bar{t}$ and single-top
  - Prompt isolated leptons from W decays
  - Large E_T^{miss} and jet(s)
- Diboson processes
  - Each diboson process is a background to the others





- Background estimation using
  1. Data driven methods
     - MC is weak in describing fragmentation processes
     - W/Z+jets and $t\bar{t}$ usually estimated from data driven techniques
  2. MC based estimation
     - Dibosons. MC expectation and shapes enter directly in the analysis.

Cross-section measurement methodology

- 'Cut and count' analysis yields observed events
- Background estimation with data-driven and MC based methods
- Measure the total and fiducial cross-sections

Total x-section

$$\sigma_{tot} = \frac{N_{obs} - N_{bkg}}{A \times C \times L \times BR}$$

Fiducial x-section

$$\sigma_{fiducial} = \frac{N_{obs} - N_{bkg}}{C \times L}$$

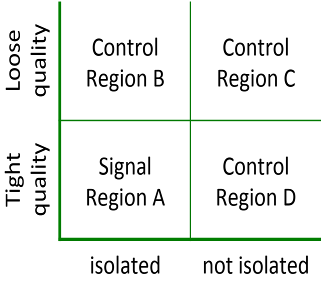
N_{obs}: number of observed events passing selection
N_{bkg}: number of estimated background events
A: acceptance
C: efficiency correction
L: integrated luminosity

BR: Branching ratio of bosons decaying to leptons

- Correct for acceptance and efficiency
  - The fiducial acceptance is calculated from truth objects imposing all analysis cuts

Background estimation methodology

- Data-driven techniques used for backgrounds containing jets
- Based on the concept of defining control regions in data enriched in the background one wishes to estimate
  - Defined by reversing analysis cuts (e.g isolation, E_T^{miss}, impact parameter significance)



Example:Fake Factor

- The probability of a jet mimicking a lepton
- Used to extrapolate the background from the control to signal region

Example:ABCD method

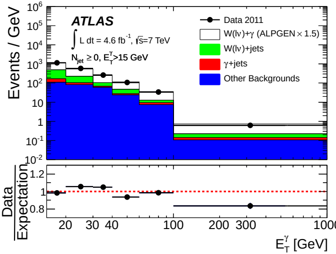
- Background expectation inferred from ratios of 2 uncorrelated variables
- $N_A \sim N_B \frac{N_C}{N_D}$

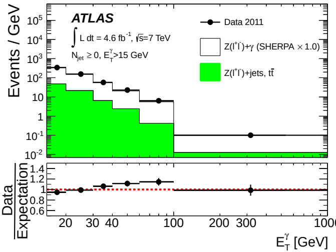
$Z\gamma, W\gamma$ cross-section measurements

- Analyses of $l\nu\gamma$, $l^+l^-\gamma$ and $\nu\nu\gamma$ final states
- Backgrounds from $W/Z + jets$(dominant), γ+jets, $t\bar{t}, WW$

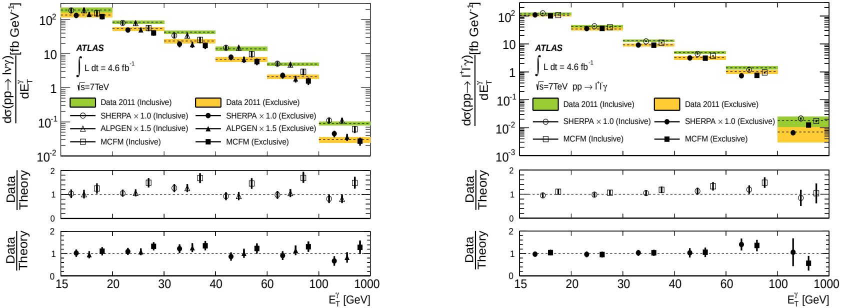
Selection highlights

- Require an isolated high-E_T photon and isolated high-p_T lepton(s)
- Suppress FSR cutting on angular separation of lepton and photon $\Delta R > 0.7$
- For exclusive measurement veto jets with $p_T > 30 GeV$





$Z\gamma, W\gamma$ cross-section results



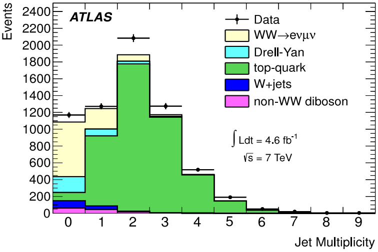
- Alpgen (Sherpa) includes LO diagram for $W + \gamma +$ up to 5 partons (V+γ+ up to 3 partons). They can describe the Vγ kinematic distribution in data quite well.
- Inclusive $W\gamma$ measurement above NLO theoretical prediction (from MCFM generator)
- Systematic uncertainty dominates (photon ID, backg normalisation, jet energy scale)
- Fair agreement for $Z\gamma$

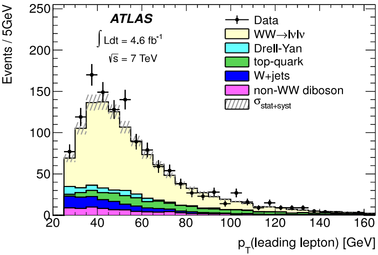
WW cross-section measurement

- Analyses of $l^+\nu l^-\nu$ final states
- Backgrounds from Drell-Yan, $W + jets$, $t\bar{t}$ and single-t, dibosons

Selection highlights

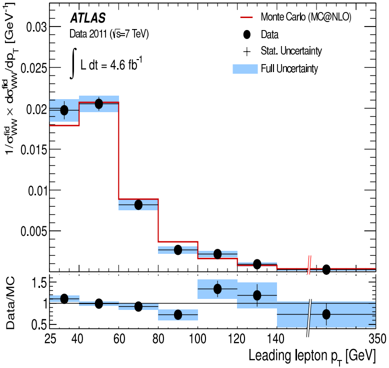
- Apply Z veto ($|m_Z - m_{ll}| > 15 GeV$) to suppress Drell-Yan background
- Apply hard jet veto to reject $t\bar{t}$ and single-top events
- Require exactly two isolated leptons and large E_T^{miss}





WW cross-section results

- Using unfolded distributions
- Total cross-section:
  - $51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 2.0(lumi) pb$
- Theory:
  - $44.7^{+2.1}_{-1.9} pb$
- Measurement slightly higher than theoretical prediction (MCFM generator)
- Higgs contribution of the order of 3% (not considered in this plot)

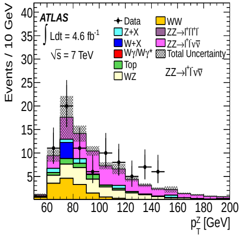


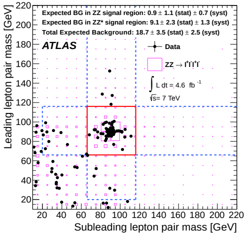
ZZ cross-section measurement

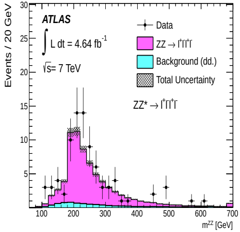
- Analyses of 4l and 2l2ν final states
- Very clean signature
- Backgrounds only significant for 2l2ν process: Drell-Yan, $t\bar{t}$, dibosons

Selection highlights

- 4l: 4 isolated high-p_T leptons - enhanced muon acceptance $|\eta| < 2.7$
- 2l2ν: Require axial-$E_T^{miss} > 80 GeV$ to suppress Drell-Yan background (for 2l2ν)
- 2l2ν: Apply jet veto $p_T > 25 GeV$ to reject $t\bar{t}$ events

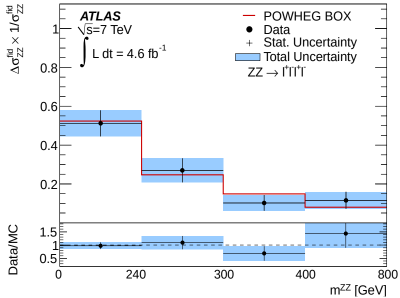


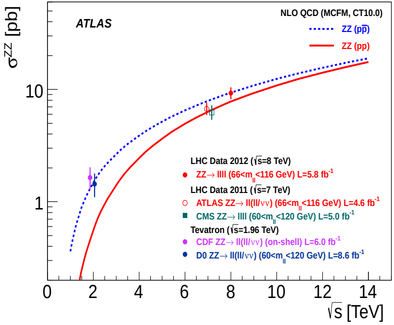




ZZ cross-section results

- Statistical uncertainty dominant
- 7 TeV analysis:
  - Using unfolded distributions
  - Total cross-section: 6.7 ± 0.7 (stat) $\pm\,^{+0.4}_{-0.3}$ (syst) $\pm$ 0.3 (lumi)pb
  - Theoretical cross-section: $5.89^{+0.22}_{-0.18} pb$





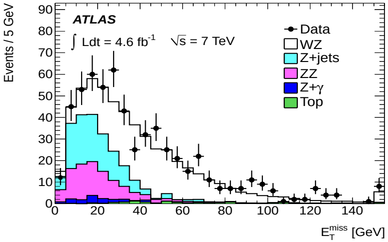
- 8 TeV analysis:
  - Total cross-section: $9.3^{+1.1}_{-1.0}$ (stat)$^{+0.4}_{-0.3}$(syst) $\pm 0.3(lumi) pb$
  - Theoretical cross-section: $7.4^{+0.4}_{-0.4} pb$

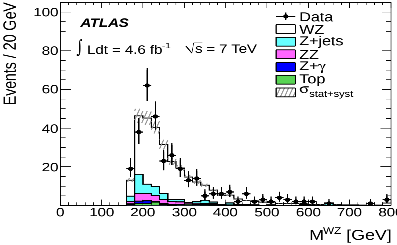
WZ cross-section measurement

- Analyses of $3l\nu$ final states
- Backgrounds $Z + jets$, $t\bar{t}$ and ZZ

Selection highlights

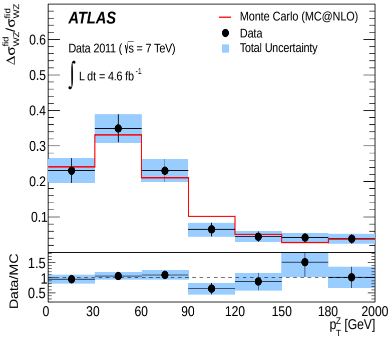
- 3 isolated high-p_T leptons, $E_T^{miss} > 25 GeV$
- Tight Z mass window requirement ($|M_{ll} - M_{pdg}| < 10 GeV$)
- Tight isolation and ID criteria on the W-lepton

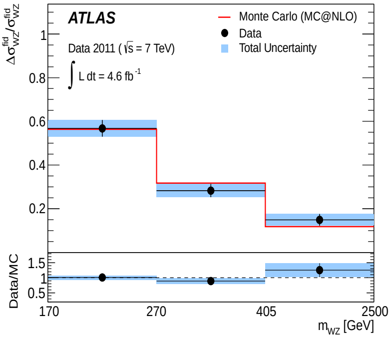




WZ cross-section results

- Using unfolded distributions
- Total cross-section:
  - $19.0^{+1.4}_{-1.3}(stat) \pm 0.9(syst) \pm 0.4(lumi)pb$
- Theoretical cross-section:
  - $17.6^{+1.1}_{-1.0}$
- Statistical uncertainty dominant





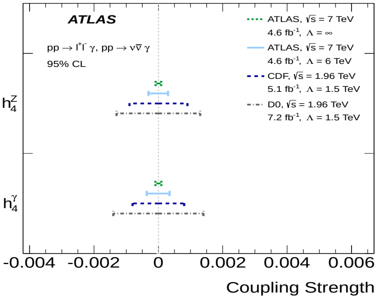
Anomalous couplings

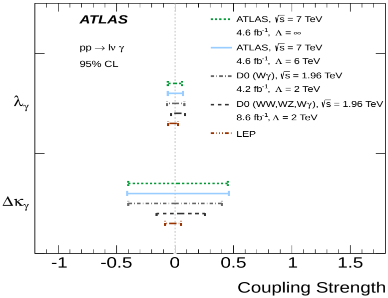
- The s-channel diagrams contain the triple gauge coupling vertex
- New physics may modify these couplings.
- Effect of aTGCs are modelled using an effective Lagrangian which depends on few parameters

coupling	parameters	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z, $\Delta\kappa_Z$,Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z , h_4^Z	Zγ
$Z\gamma\gamma$	h_3^γ, h_4^γ	Zγ
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ

- aTGCs modify total production rates and kinematics
- Increase of cross section at high invariant mass and high transverse momentum
- Neutral TGC are not allowed in the SM
- In SM all parameters are 0 except g_1^V and κ^V which are 1

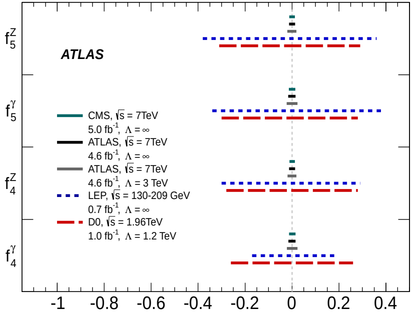
aTGC in $W\gamma$,$Z\gamma$





- Analysis on 2011 dataset
- Study performed where highest sensitivity is expected → highest E_T^γ bin
- Make use of exclusive $V\gamma$ measurement (with jet veto) in high photon E_T regions($>$100 GeV)
- No deviation from SM seen

aTGC in ZZ

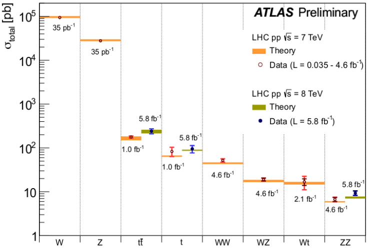


- Analysis on 2011 dataset
- No deviation from SM values observed
- Significantly tighter limits than LEP and D0

Conclusions

- Excellent performance of the LHC has provided high quality/quantity data
- Studies on diboson production utilised 7 and 8 TeV dataset. More results in the pipeline!

- Cross-section measurements
  - Measurements have been performed in WW,ZZ,WZ,Wγ and Zγ channels
  - SM predictions verified in all channels



- aTGC measurements
  - All diboson channels investigated with no apparent deviation from SM prediction
  - Limited statistics does not allow to probe deeper
  - Sensitivity is expected to increase with increased centre-of-mass energy and integrated luminosity

Backup slides

$Z/W\gamma$ selections and fiducial volume

- Single lepton or photon triggers:
  - Electrons: 20-22 GeV
  - Muons: 18 GeV
  - Photons: 80 GeV
- $|d_0|/\sigma_{d_0} < 10(3)$ e(μ)
- $|z_0| < 1mm$
- Calorimeter isolation in cone $\Delta R < 0.3$ less than 6 GeV (e)
- p_T isolation in cone $\Delta R < 0.3$ less than 15% of the μ p_T
- $W\gamma$ modelled with ALPGEN (CTEQ6L1)
- $Z\gamma, \nu\nu\gamma$ modelled with Sherpa (CTEQ6.6M)

Cuts	$pp \to \ell\nu\gamma$	$pp \to \ell^+\ell^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	—
	$\|\eta_\ell\| < 2.47$	$\|\eta_\ell\| < 2.47$	—
	$N_\ell = 1$	$N_{\ell^+} = 1, N_{\ell^-} = 1$	$N_\ell = 0$
	$p_T^\nu > 35$ GeV	—	—
Boson	—	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 90$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 100$ GeV
	$\|\eta^\gamma\| < 2.37, \Delta R(\ell,\gamma) > 0.7$		
	$\epsilon_h^p < 0.5$		
Jet	$E_T^{\text{jet}} > 30$ GeV, $\|\eta^{\text{jet}}\| < 4.4$		
	$\Delta R(e/\mu/\gamma, \text{jet}) > 0.3$		
	Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$		

$Z/W\gamma$ event yields and x-section results

	$e\nu\gamma$ ($N_{jet} \geq 0$)	$\mu\nu\gamma$ ($N_{jet} \geq 0$)	$e\nu\gamma$ ($N_{jet} = 0$)	$\mu\nu\gamma$ ($N_{jet} = 0$)
$N^{obs}_{W\gamma}$	7399	10914	4449	6578
$W(\ell\nu)$+jets	$1240 \pm 160 \pm 210$	$2560 \pm 270 \pm 580$	$910 \pm 160 \pm 160$	$1690 \pm 210 \pm 270$
$Z(\ell^+\ell^-)+X$	$678 \pm 18 \pm 86$	$779 \pm 19 \pm 93$	$411 \pm 13 \pm 51$	$577 \pm 16 \pm 73$
γ+jets	$625 \pm 80 \pm 86$	$184 \pm 9 \pm 15$	$267 \pm 79 \pm 54$	$87 \pm 7 \pm 14$
$t\bar{t}$	$320 \pm 8 \pm 28$	$653 \pm 11 \pm 57$	$22 \pm 2 \pm 4$	$44 \pm 3 \pm 6$
other background	$141 \pm 16 \pm 13$	$291 \pm 29 \pm 26$	$52 \pm 5 \pm 6$	$140 \pm 22 \pm 18$
$N^{sig}_{W\gamma}$	$4390 \pm 200 \pm 250$	$6440 \pm 300 \pm 590$	$2780 \pm 190 \pm 180$	$4040 \pm 230 \pm 280$

	$e^+e^-\gamma$ ($N_{jet} \geq 0$)	$\mu^+\mu^-\gamma$ ($N_{jet} \geq 0$)	$e^+e^-\gamma$ ($N_{jet} = 0$)	$\mu^+\mu^-\gamma$ ($N_{jet} = 0$)
$N^{obs}_{Z\gamma}$	1908	2756	1417	2032
$N^{BG}_{Z\gamma}$	$311 \pm 57 \pm 68$	$366 \pm 83 \pm 73$	$156 \pm 43 \pm 32$	$244 \pm 41 \pm 49$
$N^{sig}_{Z\gamma}$	$1600 \pm 71 \pm 68$	$2390 \pm 97 \pm 73$	$1260 \pm 56 \pm 32$	$1790 \pm 59 \pm 49$

	$\sigma^{ext-fid}$[pb] Measurement	$\sigma^{ext-fid}$[pb] MCFM Prediction
	$N_{jet} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{jet} = 0$	
$e\nu\gamma$	1.77 ± 0.04 (stat) ± 0.24 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\mu\nu\gamma$	1.74 ± 0.04 (stat) ± 0.22 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$e^+e^-\gamma$	1.07 ± 0.03 (stat) ± 0.12 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\mu^+\mu^-\gamma$	1.04 ± 0.03 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009

$Z/W\gamma$ systematic uncertainties

Systematic uncertainties on $C_{V\gamma}$

Source	$pp \to e\nu\gamma$	$pp \to \mu\nu\gamma$	$pp \to e^+e^-\gamma$	$pp \to \mu^+\mu^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Relative systematic uncertainties on the signal correction factor $C_{V\gamma}$ [%]					
γ identification efficiency	6.0 (6.0)	6.0 (6.0)	6.0 (6.0)	6.0 (6.0)	5.3 (5.3)
γ isolation efficiency	1.9 (1.8)	1.9 (1.7)	1.4 (1.4)	1.4 (1.4)	2.8 (2.8)
Jet energy scale	0.4 (2.9)	0.4 (3.2)	- (2.2)	- (2.4)	0.6 (2.0)
Jet energy resolution	0.4 (1.5)	0.6 (1.7)	- (1.7)	- (1.8)	0.1 (0.5)
unassociated energy cluster in $E_{\mathrm{T}}^{\mathrm{miss}}$	1.5 (1.6)	0.5 (1.0)	- (-)	- (-)	0.3 (0.2)
μ momentum scale and resolution	- (-)	0.5 (0.4)	- (-)	1.0 (0.8)	- (-)
EM scale and resolution	2.3 (3.0)	1.3 (1.6)	2.8 (2.8)	1.5 (1.5)	2.6 (2.7)
Lepton identification efficiency	1.5 (1.6)	0.4 (0.4)	2.9 (2.5)	0.8 (0.8)	- (-)
Lepton isolation efficiency	0.8 (0.8)	0.3 (0.2)	2.0 (1.6)	0.5 (0.4)	- (-)
Trigger efficiency	0.8 (0.1)	2.2 (2.1)	0.1 (0.1)	0.6 (0.6)	1.0 (1.0)
Total	7.1 (8.0)	6.8 (7.8)	7.6 (7.9)	6.5 (7.1)	6.6 (7.0)

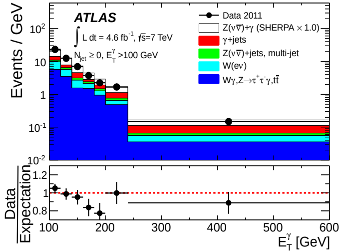
Systematic uncertainties on $A_{V\gamma}$

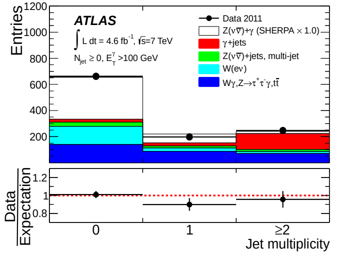
- PDF: $\sim$0.8% estimated using the CT10 error eigenvectors at their 90% CL limits rescaled to 68% CL with variation of $\alpha_s in 0.116 - 0.120$
- Scale μ_F,μ_R: $\sim$0.5% obtained by varying $\times$2 around their nominal value

Systematic uncertainties on parton-level x-section

- PDF: 3%-4%
- Scale μ_F,μ_R: 3%-7%
- γ isolation definition: 1%-5%

$\nu\nu\gamma$ final states





	$\nu\bar{\nu}\gamma$ $N_{\text{jet}} \geq 0$	$\nu\bar{\nu}\gamma$ $N_{\text{jet}} = 0$
$N_{Z\gamma}^{\text{obs}}$	1094	662
$W(e\nu)$	$171 \pm 2 \pm 17$	$132 \pm 2 \pm 13$
$Z(\nu\bar{\nu})$+jets, multi-jet	$70 \pm 13 \pm 14$	$29 \pm 5 \pm 3$
$W\gamma$	$238 \pm 12 \pm 37$	$104 \pm 9 \pm 24$
γ+jets	$168 \pm 20 \pm 42$	$26 \pm 7 \pm 11$
$Z(\tau^+\tau^-)\gamma$	$11.7 \pm 0.7 \pm 0.9$	$6.5 \pm 0.6 \pm 0.6$
$t\bar{t}$	$11 \pm 1.2 \pm 1.0$	$0.9 \pm 0.6 \pm 0.1$
$N_{Z\gamma}^{\text{sig}}$	$420 \pm 42 \pm 60$	$360 \pm 29 \pm 30$

aTGCs in $W/Z\gamma$

	Measured	Expected
processes	$pp \to \ell\nu\gamma$	
Λ	∞	∞
$\Delta\kappa_\gamma$	$(-0.41, 0.46)$	$(-0.38, 0.43)$
λ_γ	$(-0.065, 0.061)$	$(-0.060, 0.056)$
Λ	6 TeV	6 TeV
$\Delta\kappa_\gamma$	$(-0.41, 0.47)$	$(-0.38, 0.43)$
λ_γ	$(-0.068, 0.063)$	$(-0.063, 0.059)$
processes	$pp \to \nu\nu\gamma$ and $pp \to \ell^+\ell^-\gamma$	
Λ	∞	∞
h_3^γ	$(-0.015, 0.016)$	$(-0.017, 0.018)$
h_3^Z	$(-0.013, 0.014)$	$(-0.015, 0.016)$
h_4^γ	$(-0.000094, 0.000092)$	$(-0.00010, 0.00010)$
h_4^Z	$(-0.000087, 0.000087)$	$(-0.000097, 0.000097)$
Λ	3 TeV	3 TeV
h_3^γ	$(-0.023, 0.024)$	$(-0.027, 0.028)$
h_3^Z	$(-0.018, 0.020)$	$(-0.022, 0.024)$
h_4^γ	$(-0.00037, 0.00036)$	$(-0.00043, 0.00042)$
h_4^Z	$(-0.00031, 0.00031)$	$(-0.00037, 0.00036)$

$WW/WZ \rightarrow l\nu jj$ cross-section measurement

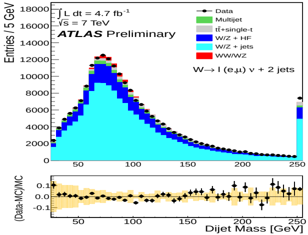
- Analyses of semi-leptonic final state
- Main backgrounds $W, Z + jets$, $t\bar{t}$ and other dibosons

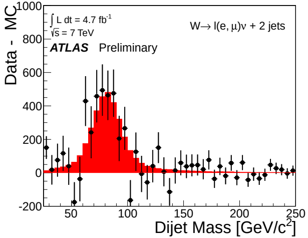
Selection highlights

- Exactly 1 reconstructed lepton suppresses Z+jets background
- Restrict multi-jet background by requiring exactly 2 jets and angular separation of leading jet and E_T^{miss} of $\Delta\phi(E_T^{miss}, j_1) > 0.8$

Cross-section results

$\sigma(WW + WZ) =$
$72 \pm 9(stat.) \pm 15(syst.) \pm 13(MCstat.) pb$, consistent with the Standard Model expectation of $63.4 \pm 2.6 pb$





WW Event Selection

- Single lepton triggers:
  - Electrons: 20-22 GeV
  - Muons: 18 GeV
- $p_T > 20 GeV$
- $|d_0|/\sigma_{d_0} < 10(3)$ e(μ)
- $|z_0| < 1mm$

- Calorimeter isolation in cone $\Delta R < 0.3$ less than 14% of the lepton p_T
- p_T isolation in cone $\Delta R < 0.3$ less than 13%(15%) of the e (μ) p_T
- $|m_{ll} - m_Z| > 15, 15, 0(ee, \mu\mu, e\mu)$
- $E_{T,rel}^{miss} > 45, 45, 25(ee, \mu\mu, e\mu)$
- jet veto ($p_T > 25 GeV$, $|\eta| < 4.5$)

WW Event yield and x-section result

Event yield

	ee	$\mu\mu$	$e\mu$	Combined
Data	174	330	821	1325
WW	100±2±9	186±2±15	538±3±45	824±4±69
Top	22±12±3	32±14±5	87±23±13	141±30±22
W+jets	21±1±11	7±1±3	70±2±31	98±2±43
Drell-Yan	12±3±3	34±6±10	5±2±1	51±7±12
Other dibosons	13±1±2	21±1±2	44±2±6	78±2±10
Total background	68±12±13	94±15±13	206±24±35	369±31±53
Total expected	169±12±16	280±16±20	744±24±57	1192±31±87

Cross-section results

	Measured σ^{fid}_{WW} (fb)	Predicted σ^{fid}_{WW} (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$56.4 \pm 6.8 \pm 9.8 \pm 2.2$	54.6 ± 3.7	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	44.7 ± 2.8
$\mu\mu$	$73.9 \pm 5.9 \pm 6.9 \pm 2.9$	58.9 ± 4.0	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	44.7 ± 2.8
$e\mu$	$262.3 \pm 12.3 \pm 20.7 \pm 10.2$	231.4 ± 15.7	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	44.7 ± 2.8
Combined	...	...	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	44.7 ± 2.8

WW systematic uncertainties

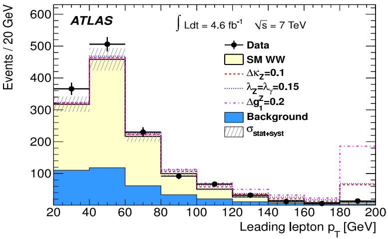
Aww

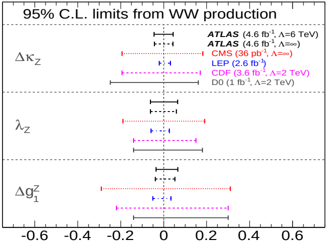
Source of uncertainty	Relative uncertainty ee	$\mu\mu$	$e\mu$
PDFs	0.9%	0.9%	0.9%
μ_R and μ_F scales	0.5%	0.5%	0.6%
Jet veto	5.6%	5.6%	5.6%
Total	5.7%	5.7%	5.7%

Cww

Source of uncertainty	Relative uncertainty ee	$\mu\mu$	$e\mu$
Trigger efficiency	0.1%	0.6%	0.3%
Lepton efficiency	2.9%	0.7%	1.4%
Lepton p_T scale and resolution	0.9%	0.8%	0.6%
Jet energy scale and resolution	0.6%	0.5%	0.5%
E_T^{miss} modeling	0.5%	0.2%	0.4%
Jet veto scale factor	2.8%	2.8%	2.7%
PDFs, μ_R and μ_F scales	0.7%	0.7%	0.3%
Total	4.2%	3.1%	3.2%

aTGC in WW





- Analysis on full 2011 dataset
- Maximum likelihood fit performed for events in bin $p_T^{lep} > 120 GeV$
- No sign of deviation from SM predictions

Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
$\Delta\kappa_Z$	$[-0.077, 0.086]$	$[-0.078, 0.092]$
λ_Z	$[-0.071, 0.069]$	$[-0.074, 0.073]$
λ_γ	$[-0.144, 0.135]$	$[-0.152, 0.146]$
Δg_1^Z	$[-0.449, 0.546]$	$[-0.373, 0.562]$
$\Delta\kappa_\gamma$	$[-0.128, 0.176]$	$[-0.135, 0.190]$

TGC scenarios in WW

- Equal Couplings scenario assumes WWZ and $WW\gamma$ are equal. $(\Delta\kappa_z = \Delta\kappa_\gamma, \lambda_Z = \lambda_\gamma, g_1^Z = 1)$
- LEP scenario assumes $\Delta\kappa_\gamma = (cos^2\theta_W / sin^2\theta_W)(\Delta g_1^Z - \Delta\kappa_Z)$ and $\lambda_Z = \lambda_\gamma$
- HISZ scenario assumes $\Delta g_1^Z = \Delta\kappa_Z/(cos^2\theta_W - sin^2\theta_W)$, $\Delta\kappa_\gamma = 2\Delta\kappa_Z cos^2\theta_W/(cos^2\theta_W - sin^2\theta_W)$ and $\lambda_Z = \lambda_\gamma$

ZZ event selection and yields

- $p_T > 7GeV$, SA muons
  $p_T > 10GeV$, calo muons and fwd e
  $p_T > 20GeV$
- Calorimeter isolation in cone $\Delta R < 0.2(0.3)$ less than 30%(15%) of the lepton p_T for $ZZ \to 4l(ZZ \to 2l2\nu)$
- p_T isolation in cone $\Delta R < 0.2(0.3)$ less than 15% of the lepton p_T for $ZZ \to 4l(ZZ \to 2l2\nu)$
- $|d_0|/\sigma_{d_0} < 6(3.5)$ e(μ)
- $|z_0| < 2mm$

$ZZ^* \to 4l$

- $\Delta R(l_1, l_2) > 0.2$
- $|m_{ll} - m_Z| < 25$ on shell $m_{ll} > 20$ off-shell

$ZZ \to 2l2\nu$

- $\Delta R(l_1, l_2) > 0.3$
- $76 < |m_{ll} - m_Z| < 106$
- axia-$E_T^{miss} > 75GeV$
- jet veto $p_T > 25GeV$

$ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Observed ZZ	16	23	27	66
Observed ZZ^*	21	30	33	84
Expected ZZ signal	$10.3 \pm 0.1 \pm 1.0$	$16.5 \pm 0.2 \pm 0.9$	$26.7 \pm 0.2 \pm 1.7$	$53.4 \pm 0.3 \pm 3.2$
Expected ZZ^* signal	$12.3 \pm 0.2 \pm 1.2$	$20.5 \pm 0.2 \pm 1.1$	$31.6 \pm 0.3 \pm 2.0$	$64.4 \pm 0.4 \pm 4.0$
Expected ZZ background	$0.5 \pm 0.6 \pm 0.3$	< 0.6	$0.7 \pm 0.7 \pm 0.6$	$0.9 \pm 1.1 \pm 0.7$
Expected ZZ^* background	$4.3 \pm 1.4 \pm 0.6$	< 0.9	$5.8 \pm 1.6 \pm 0.9$	$9.1 \pm 2.3 \pm 1.3$

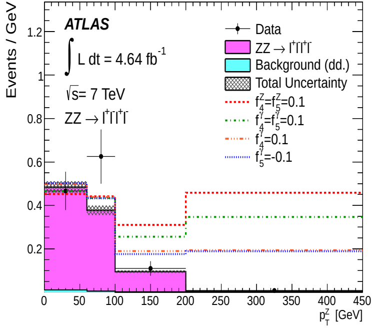
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$e^+e^-E_T^{miss}$	$\mu^+\mu^-E_T^{miss}$		$\ell^+\ell^-E_T^{miss}$
Observed ZZ	35	52		87

ZZ summary of systematic uncertainties

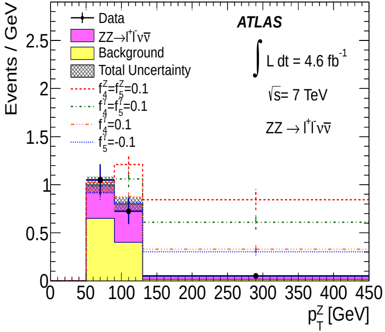
Source	$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$	$ZZ \to \ell^+\ell^-\nu\bar{\nu}$
	C_{ZZ}		
Lepton efficiency	3.0%	3.1%	1.3%
Lepton energy/momentum	0.2%	0.3%	1.1%
Lepton isolation and impact parameter	1.9%	2.0%	0.6%
Jet+E_T^{miss} modelling	–	–	0.8%
Jet veto	–	–	0.9%
Trigger efficiency	0.2%	0.2%	0.4%
PDF and scale	1.6%	1.5%	0.4%
	A_{ZZ}		
Jet veto	–	–	2.3%
PDF and scale	0.6%	–	1.9%
Generator modelling and parton shower	1.1%	–	4.6%

aTGCs in ZZ

$ZZ \to 4l$



$ZZ \to 2l2\nu$



Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
3 TeV	$[-0.022, 0.023]$	$[-0.019, 0.019]$	$[-0.023, 0.023]$	$[-0.020, 0.019]$
∞	$[-0.015, 0.015]$	$[-0.013, 0.013]$	$[-0.016, 0.015]$	$[-0.013, 0.013]$

WZ Event Selection

- $p_T > 15 GeV$ and $p_T > 20 GeV$ for the W lepton
- $|\eta| < 2.5(\mu), |\eta < 2.47|(e)$
- $|m_{ll} - m_Z| < 10$
- $E_{T,rel}^{miss} > 25 GeV$
- $m_T^W > 20 GeV$
- p_T isolation in cone $\Delta R < 0.3$ less than 13%(15%) of the e (μ) p_T
- Calorimeter isolation in cone $\Delta R < 0.3$ less than 14% of the lepton p_T
- $|d_0|/\sigma_{d_0} < 10(3)$ e(μ)
- $|z_0| < 1mm$

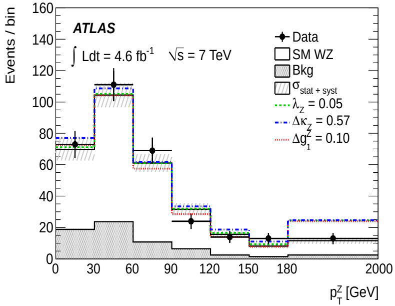
	eee	μee	$e\mu\mu$	$\mu\mu\mu$
N_{obs}	56	75	78	108
N_{sig}	38.9 ± 2.1	54.0 ± 2.2	56.6 ± 1.7	81.7 ± 2.1
N_{bkg}	14.5 ± 2.9	11.5 ± 2.5	21.0 ± 3.5	21.0 ± 5.6

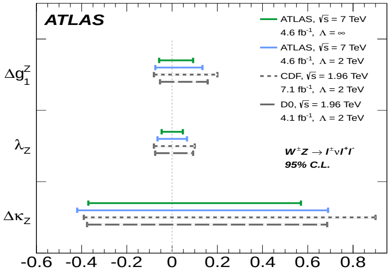
WZ summary of systematic uncertainties

Source	eee	μee	$e\mu\mu$	$\mu\mu\mu$
μ reconstruction efficiency	—	0.3	0.5	0.8
μ p_T scale & resolution	—	< 0.1	0.1	0.1
μ isolation & impact param.	—	0.2	0.4	0.6
e reconstruction efficiency	2.5	1.7	0.8	—
e identification efficiency	3.5	2.3	1.2	—
e isolation & impact param.	1.5	1.1	0.4	—
e energy scale	0.5	0.3	0.3	—
e energy resolution	0.1	0.1	< 0.1	—
E_T^{miss} cluster energy scale	0.4	0.2	0.6	0.2
E_T^{miss} jet energy scale	0.1	0.1	0.1	0.1
E_T^{miss} jet energy resolution	0.3	0.3	0.4	0.2
E_T^{miss} pile-up	0.3	0.1	0.3	0.1
Muon trigger	—	0.1	0.1	0.3
Electron trigger	< 0.1	< 0.1	< 0.1	—
Event generator	0.4	0.4	0.4	0.4
PDF	1.2	1.2	1.2	1.2
QCD scale	0.4	0.4	0.4	0.4
Luminosity	1.8	1.8	1.8	1.8

Source	σ_{WZ}^{fid}	σ_{WZ}^{tot}
μ reconstruction	0.7	0.7
e reconstruction	2.1	2.0
E_T^{miss} reconstruction	0.5	0.5
Trigger	0.2	0.2
Signal MC statistics	0.5	0.5
Background data-driven	4.0	4.0
Background MC estimates	0.4	0.4
Event generator	–	0.4
PDF	–	1.2
QCD scale	–	0.4
Total	4.6	4.8
Luminosity	1.8	1.8

aTGC in WZ





- No deviation from SM predictions observed
- Analysis performed with 2011 dataset