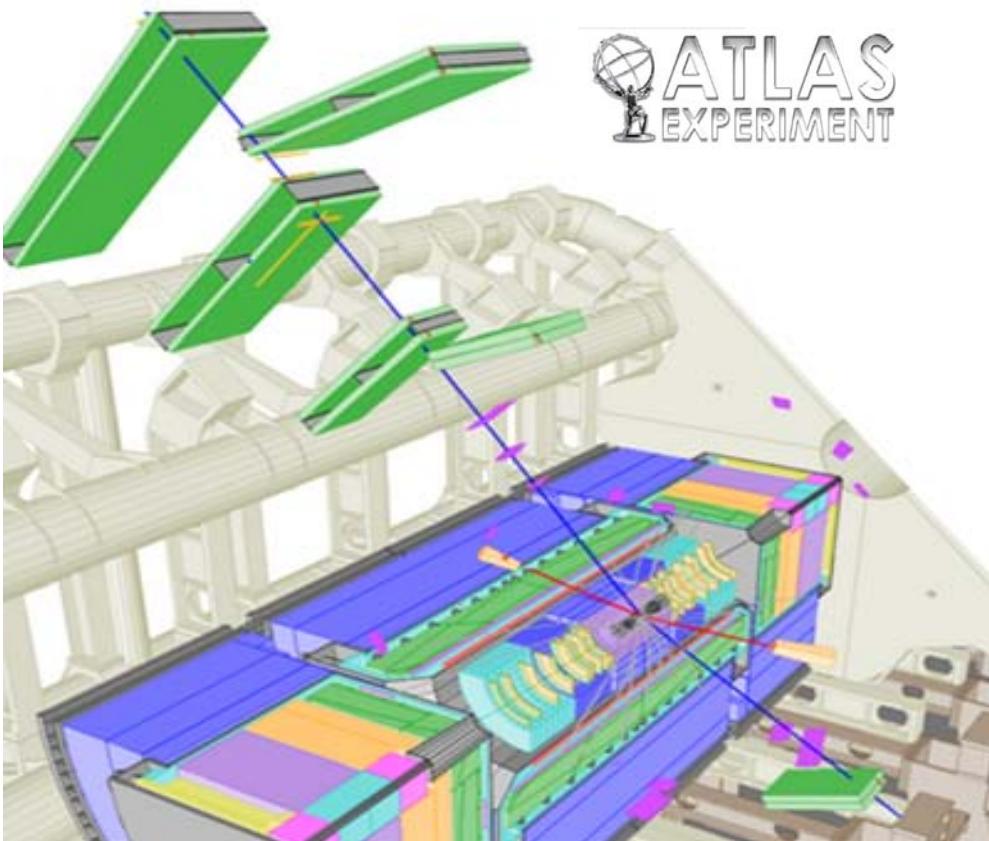


Diboson and its Triple Gauge Boson Couplings in Standard Model

LHCP 2013

Barcelona, Spain,
May 13-18th, 2013



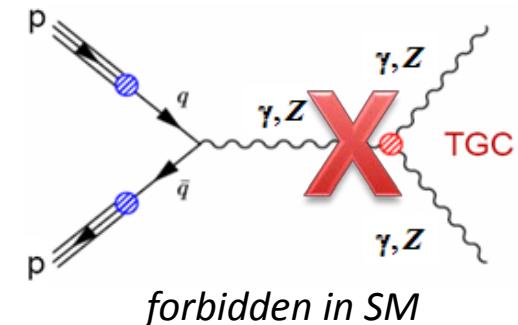
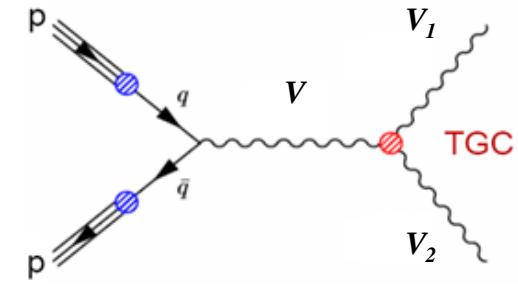
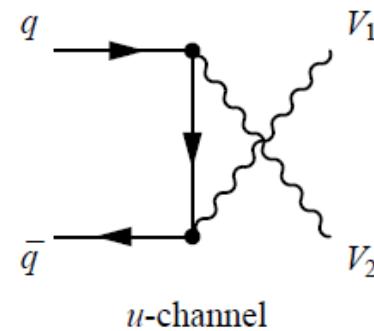
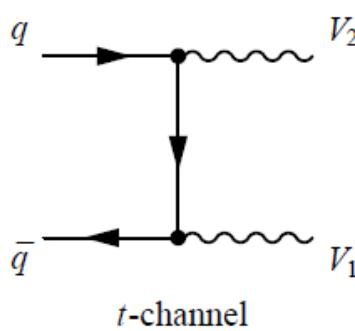
Suen Hou
Academia Sinica
for the ATLAS collab.



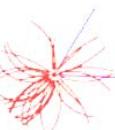


SM Diboson production

LO production diagram



- SM predicts vector boson self-interactions
- Diboson production (**WW, WZ, ZZ, W γ , Z γ**)
 - precision measurements of SM at TeV scale
 - unique probe for **Triple Gauge Couplings**
anomalous TGC indicates new physics
 - background to **Higgs** and many **searches** of new physics



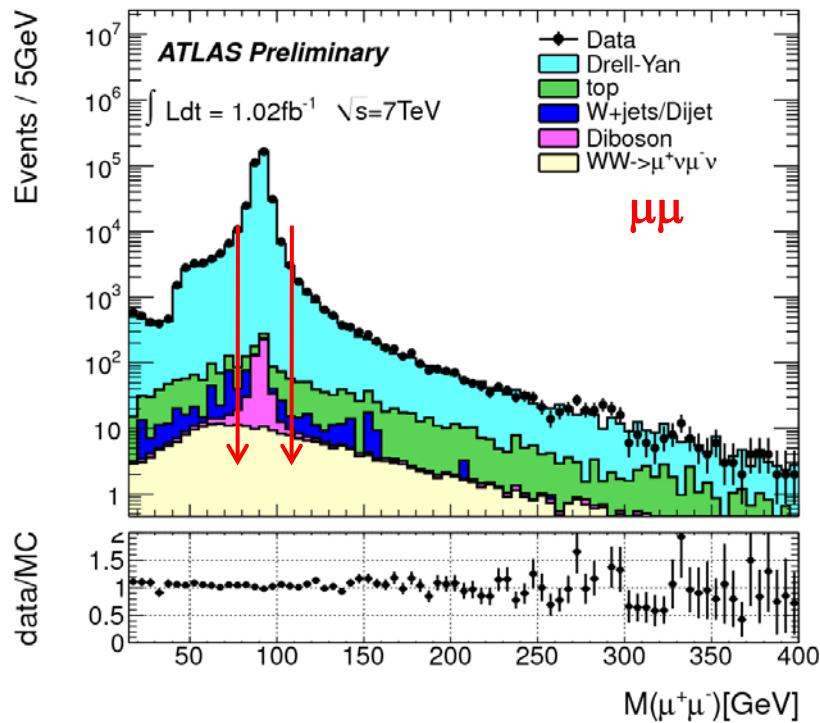
WW production

(7 TeV 4.6 fb⁻¹, arXiv 1211.2979)

Signature

$$WW \rightarrow \ell^+ \ell^- + E_T^{miss}$$

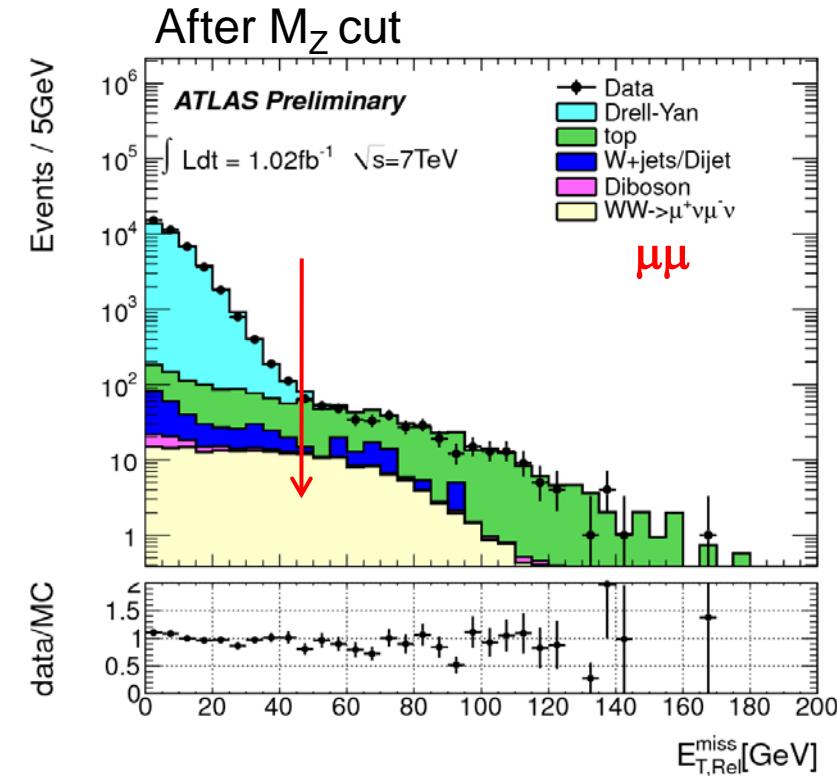
- two opposite-sign charge leptons (e, μ)
lepton $p_T > 20$ GeV
- large Missing Transverse Energy (MET)

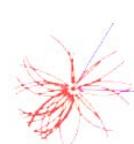


Background

Drell-Yan, Wjets, $t\bar{t}$:

- $|M_{||} - M_Z| > 15$ GeV for ee and $\mu\mu$
- $M_{||} > 10$ (15) GeV for $e\mu$, ($ee, \mu\mu$)
- $E_T^{Miss, Rel} > 25$ (45) GeV for $e\mu$, ($ee, \mu\mu$)





WW → llvv results

(7 TeV 4.6 fb⁻¹, arXiv 1211.2979)

Cross section measurement

- detector fiducial,
- full phase space,

$$\sigma_{fiducial} = \frac{N_{obs} - N_{bkgd}}{C_{WW} \times \int Ldt}$$

$$\sigma_{total} = \frac{\sigma_{fiducial}}{A_{WW} \times \mathcal{BR}}$$

Combined total cross-section (7 TeV)

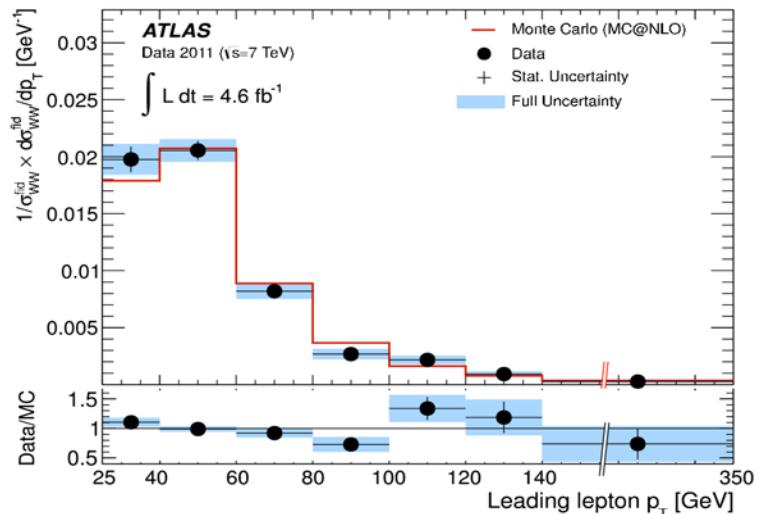
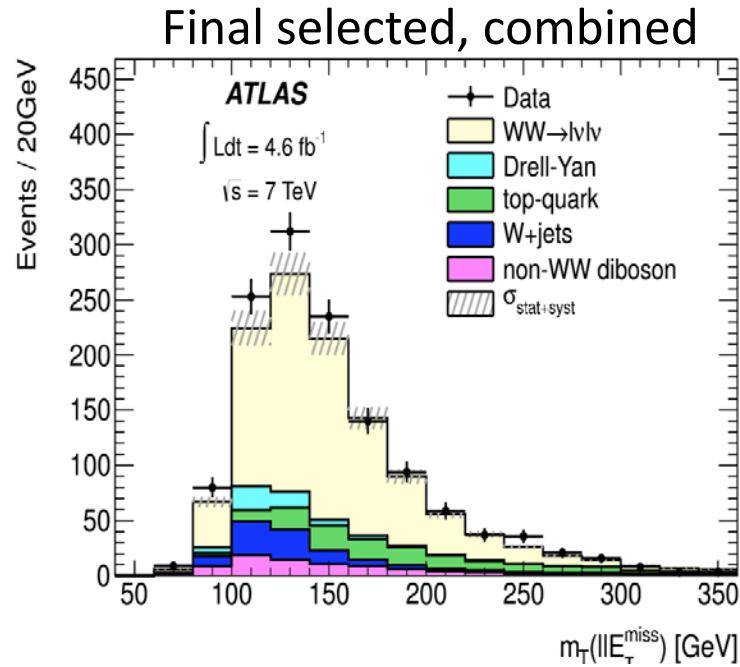
$51.9 \pm 2.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0 (\text{lumi}) \text{ pb}$

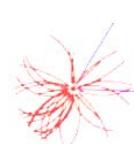
➤ compatible with NLO MCFM+CT10

$44.7^{+2.1}_{-1.9} \text{ pb}$

➤ Higgs (126GeV) contribution

$\approx 3\%$ of σ_{WW} not included in calculations





WZ production

(7 TeV 4.6 fb⁻¹, EPJC 72 (2012) 2173
 8 TeV 13 fb⁻¹, ATLAS-CONF 2013-021)

Signatures:

- tri-leptons, one Z + E_T^{miss}

Background:

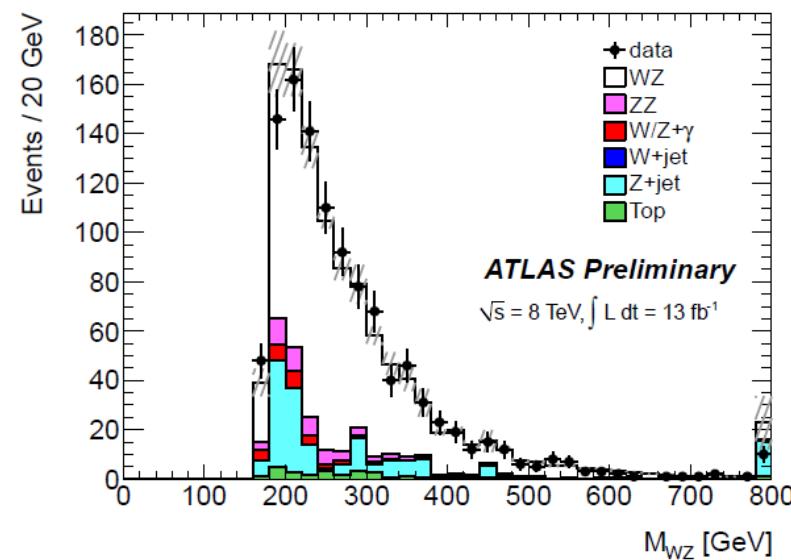
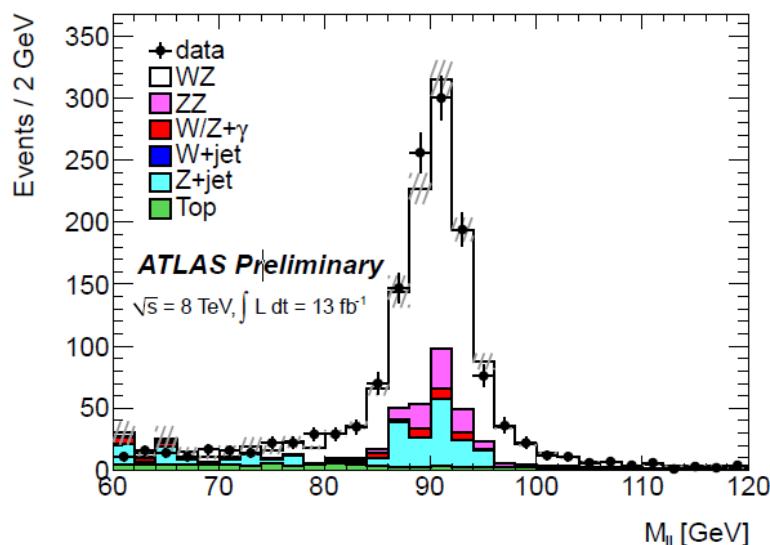
- Z+Jets, $t\bar{t}$, diboson

Selection:

- 3 high p_T leptons
 $p_T > 15 \text{ GeV}, p_T > 20 \text{ GeV}$ for W decay lepton
- event $E_T^{\text{miss}} > 25 \text{ GeV}$
- $m_T^W > 20 \text{ GeV}$
- Z mass window $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$

8 TeV 13 fb⁻¹

Final State	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$	Combined
Observed	192	270	298	334	1094
Bkg (total)	$60 \pm 4 \pm 11$	$55 \pm 4 \pm 10$	$87 \pm 5 \pm 11$	$75 \pm 5 \pm 14$	$277 \pm 9 \pm 24$
Expected signal	144 ± 12	199 ± 16	200 ± 16	276 ± 21	819 ± 34



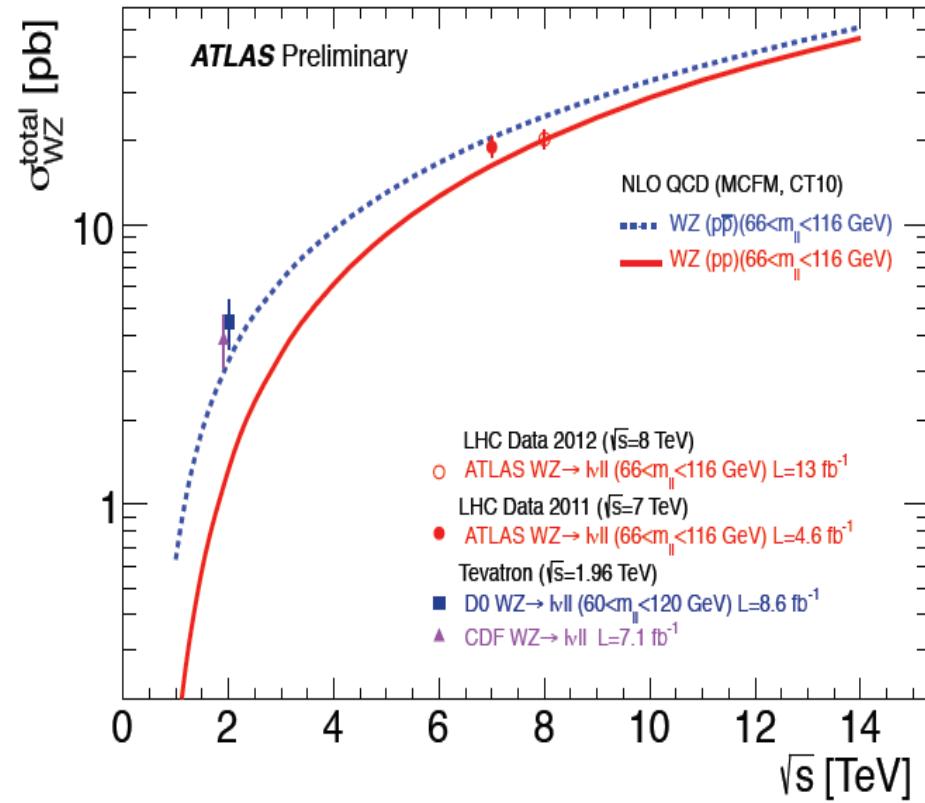
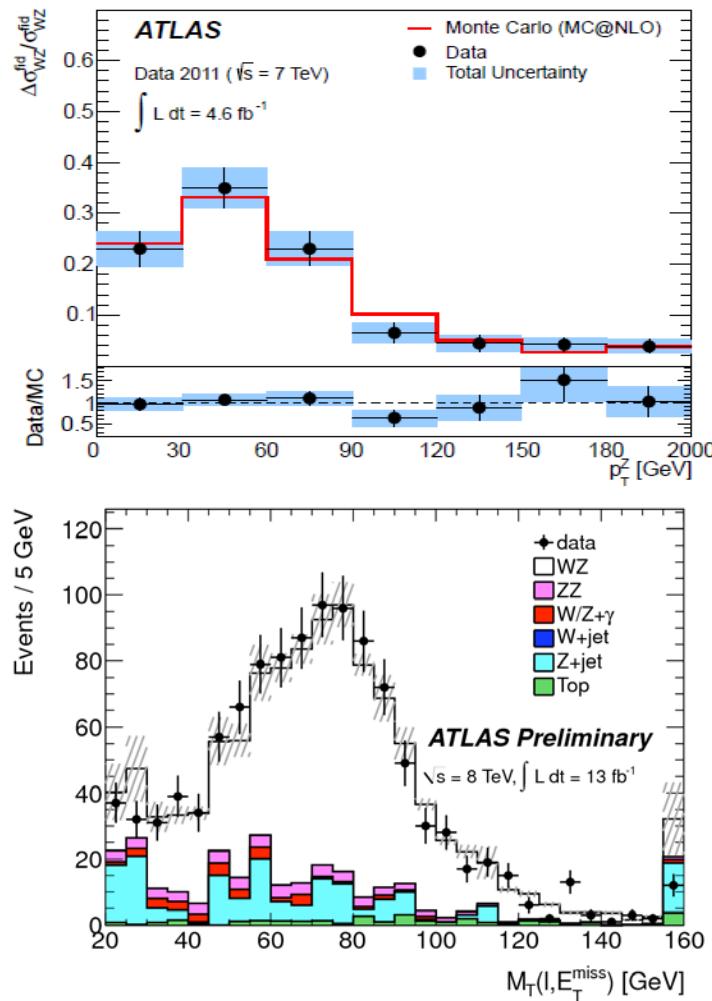
WZ results

Total cross -section

7 TeV: $19.0^{+1.4}_{-1.3}$ (stat) ± 0.9 (syst) ± 0.4 (lumi) pb
 8 TeV: $20.3^{+0.8}_{-0.7}$ (stat) $^{+1.2}_{-1.1}$ (syst) $^{+0.7}_{-0.6}$ (lumi) pb

MCFM calculations

$17.6^{+1.1}_{-1.0}$ pb
 20.3 ± 0.8 pb



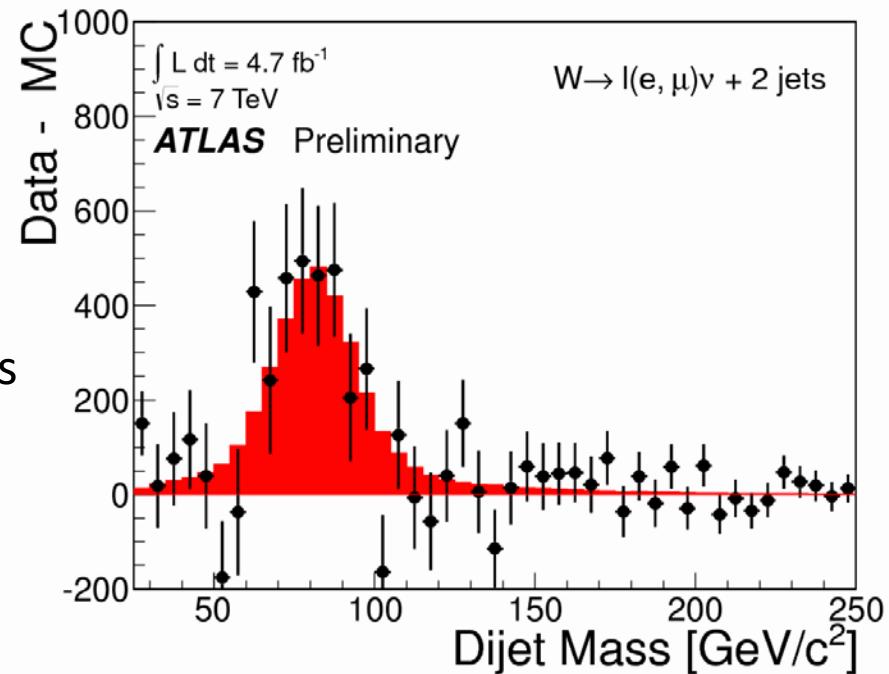
$(WW+WZ) \rightarrow \ell\nu jj$

Background:

- W/Z+Jets, $t\bar{t}$, diboson

Selection:

- exactly 1 lepton, suppress Z+jets
 - exactly 2 jets, suppress QCD multi-jets
- $p_T(j_1) > 30 \text{ GeV}, p_T(j_2) > 25 \text{ GeV}$
 $\Delta\phi(E_T^{\text{miss}}, j_1) > 0.8,$
 $\Delta R(j_1, j_2) > 0.7, |\Delta\eta(j_1, j_2)| < 1.5$
- MET> 30 GeV, $m_T > 40 \text{ GeV}$



Total cross-section measured

7 TeV: $72 \pm 9(\text{stat}) \pm 15(\text{syst}) \pm 13 \text{ (MC stat)} \text{ pb}$

MCFM $63.4 \pm 2.6 \text{ pb}$



ZZ production

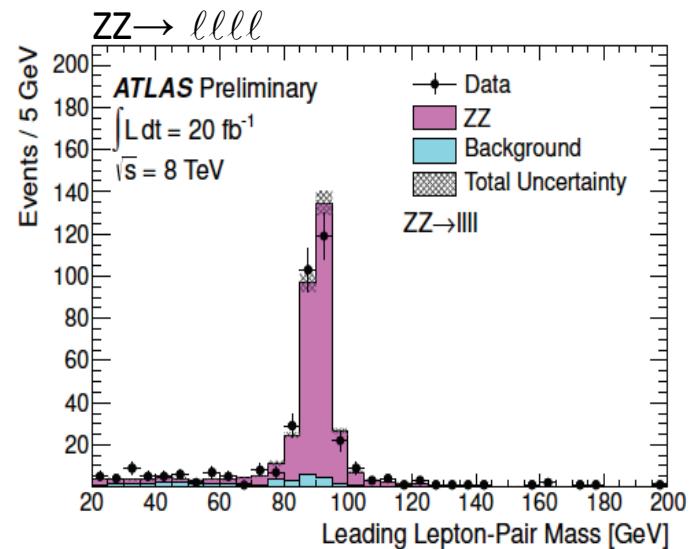
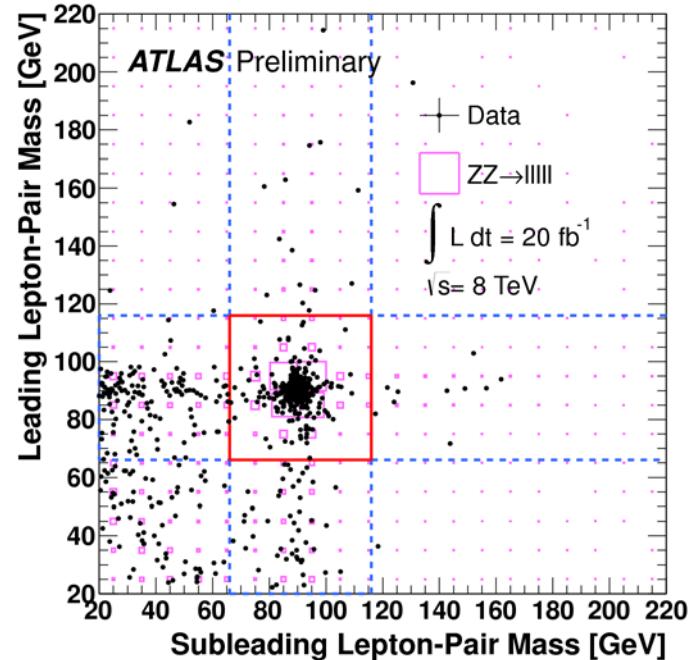
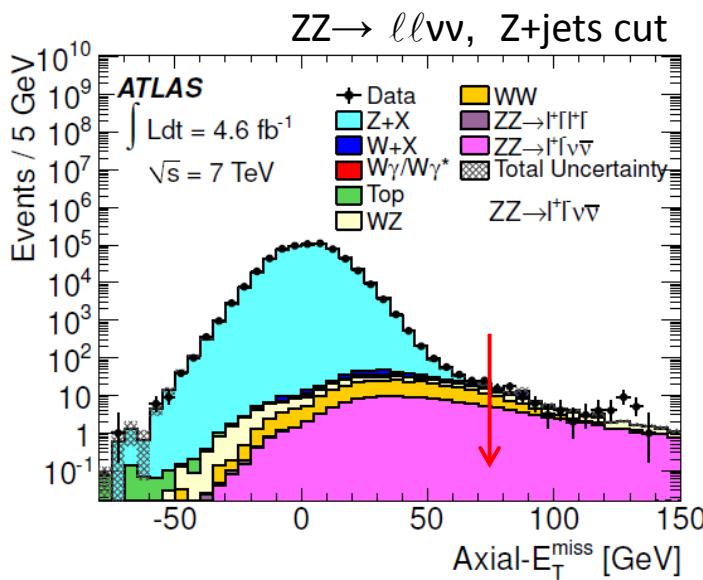
(7 TeV 4.7 fb⁻¹, JHEP03(2013)128
 8 TeV 20 fb⁻¹, ATLAS-CONF 2013-020)

Signatures:

- leptons paired into Z
- isolation, $\Delta R(\ell\ell) > 0.2$
- ZZ → $\ell\ell\ell\ell$ (8 TeV) : $66 < M_{\parallel} < 116$ GeV
- ZZ → $\ell\ell\nu\nu$ (7 TeV) : Axial $E_T^{\text{miss}} > 75$ GeV, no jet

Background:

- very clean, little background
- Z/W+Jets, $t\bar{t}$, Single top, diboson
- data-driven estimation
 relax isolation, obtain fake fraction
 extrapolate background yield





ZZ results

Measurements of total cross-sections

- 8 TeV analysis of $ZZ \rightarrow \ell\ell\ell\ell$

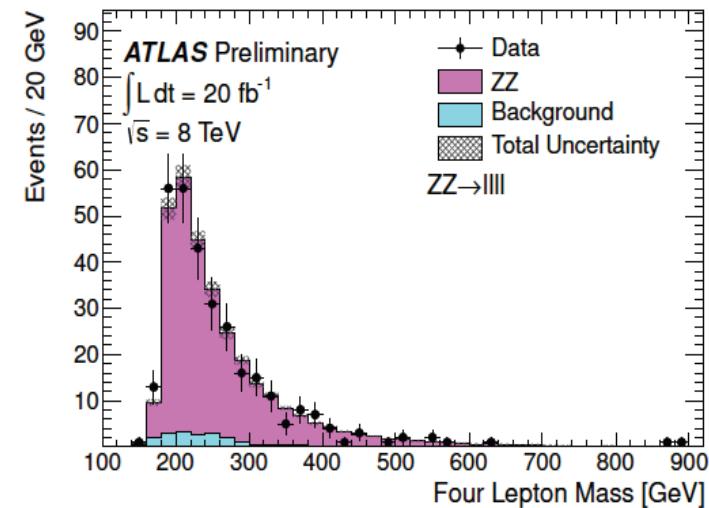
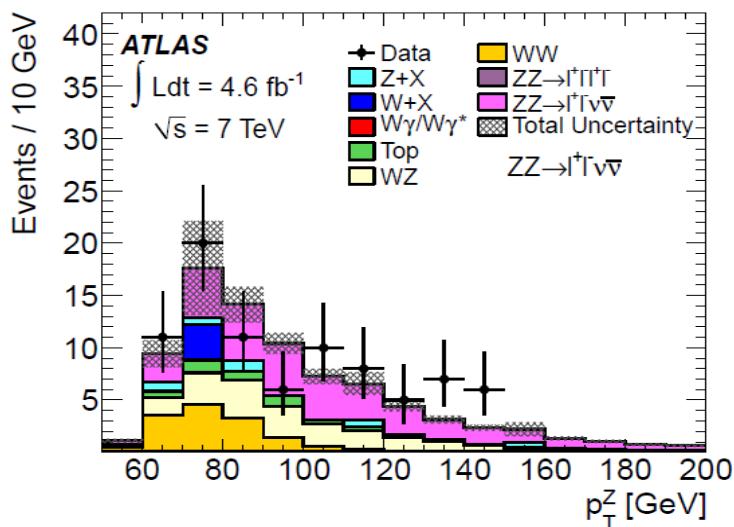
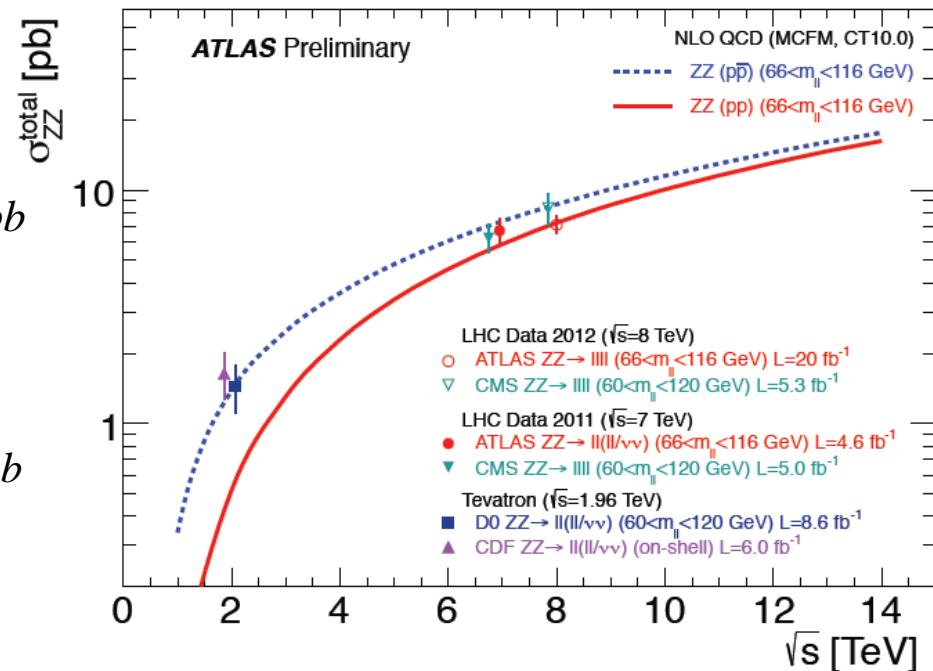
$$\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4} (stat) \pm 0.3 (syst) \pm 0.2 (lumi) \text{ pb}$$

MCFM : $7.2^{+0.3}_{-0.2} \text{ pb}$

- 7 TeV analysis of $ZZ \rightarrow \ell\ell\ell\ell, \ell\ell\nu\nu$

$$\sigma_{ZZ}^{tot} = 6.7 \pm 0.7 (stat) ^{+0.4}_{-0.3} (syst) \pm 0.3 (lumi) \text{ pb}$$

MCFM : $5.89^{+0.22}_{-0.18} \text{ pb}$

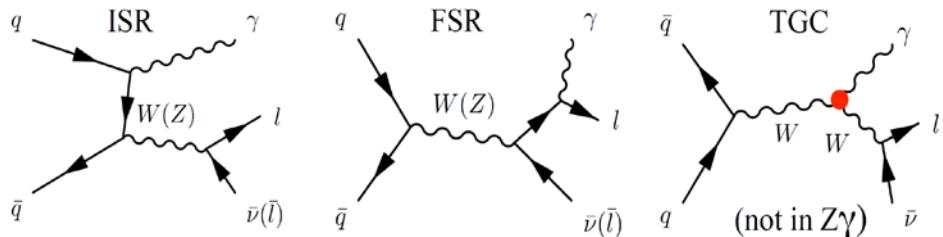


W γ , Z γ production

(7 TeV 4.6 fb $^{-1}$, arXiv: 1302.1283)

Signatures:

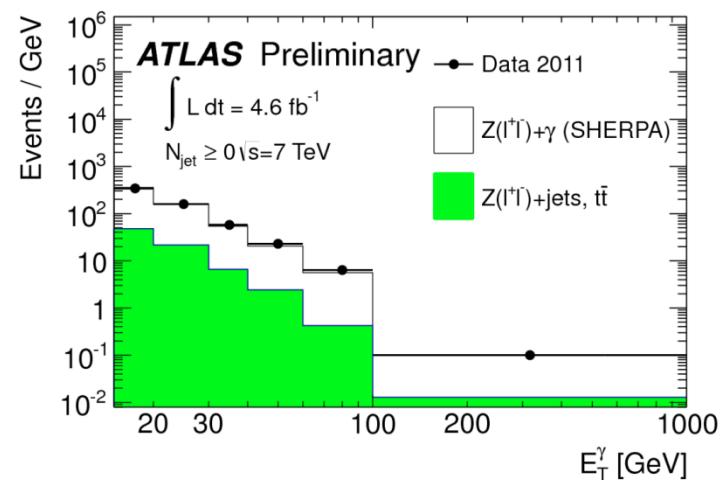
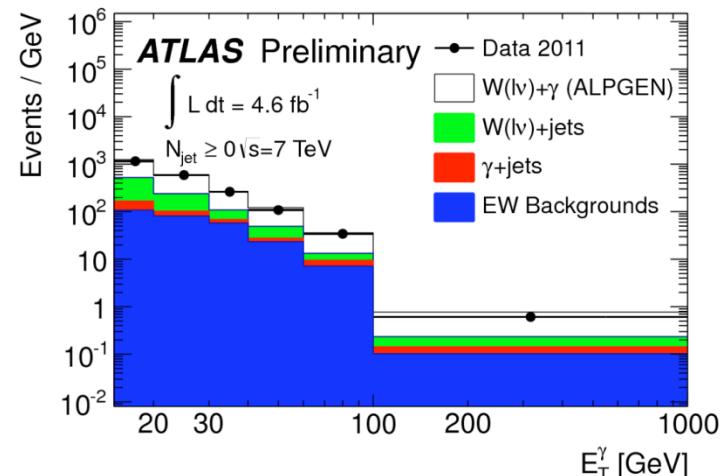
- W γ single lepton + E_T^{miss} + γ
- Z γ two lepton ($Z \rightarrow \ell\ell$) + γ ,
Z γ E_T^{miss} ($Z \rightarrow \nu\nu$) + γ



Background:

- Z/W+Jets, γ +jets, Drell-Yan
- $\Delta R(\ell, \gamma) > 0.7$ cut on FSR

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



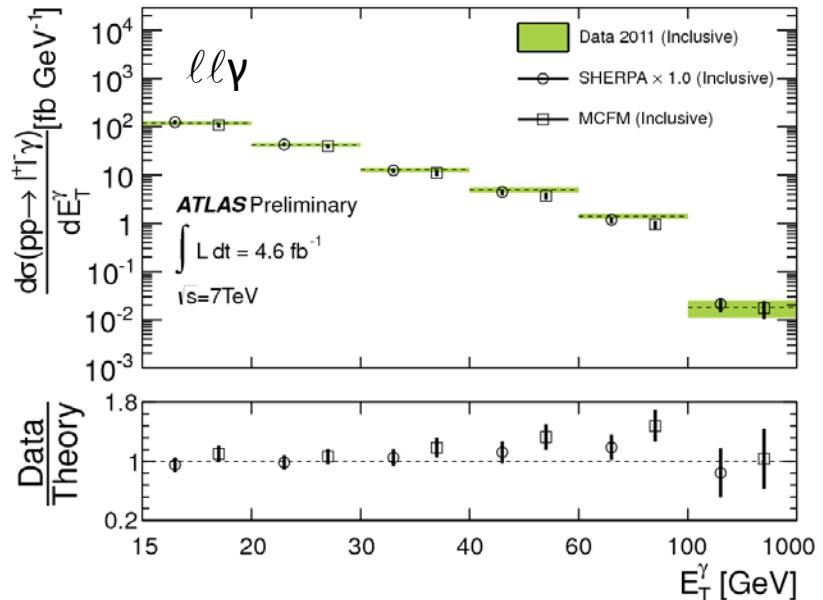
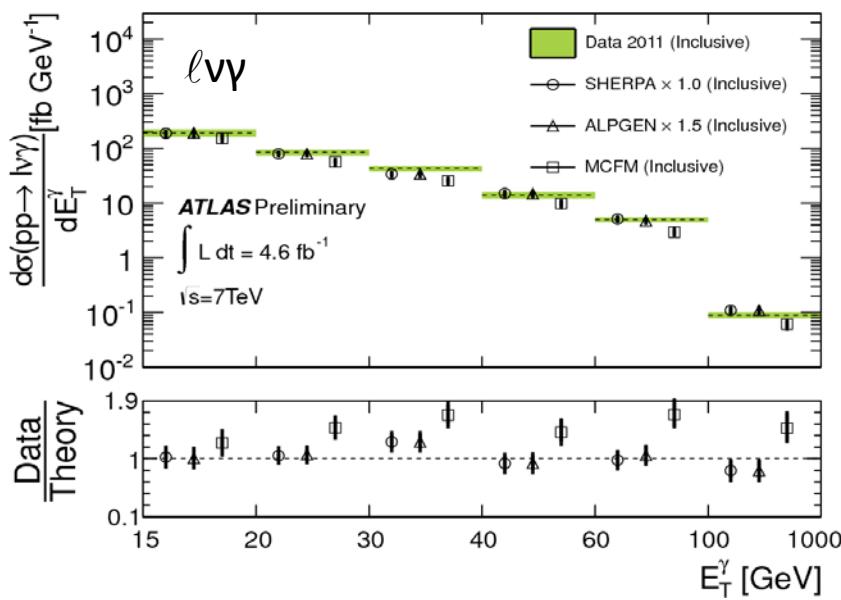
W γ , Z γ results

Cross section for W/Z γ
0-jet compatible with MCFM

Systematics ~9%

MC NLO, Lumi, bkgd estimation
Lepton/ γ ID, jet, E_T^{miss}

	Measurement	$\sigma^{\text{ext-fid}} [\text{pb}]$	$\sigma^{\text{ext-fid}} [\text{pb}]$ MCFM Prediction
		$N_{\text{jet}} \geq 0$	
$l\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17	
$l^+l^-\gamma$	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	
$N_{\text{jet}} = 0$		$\sigma^{\text{ext-fid}} [\text{pb}]$	$\sigma^{\text{ext-fid}} [\text{pb}]$ MCFM Prediction
		$l\nu\gamma$	1.39 ± 0.13
		$l^+l^-\gamma$	1.06 ± 0.05
		$\nu\bar{\nu}\gamma$	0.115 ± 0.009





anomalous TGCs

- Effective Lagrangian:
charged TGC interactions

$$L/g_{WWV} = ig_1^V(W_{\mu\nu}^*W^{\mu\nu}V^v - W_{\mu\nu}W^{*\mu}V^\nu) + ik^VW_\mu^*W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2}W_{\rho\mu}^*W_\nu^\mu V^{\nu\rho}$$

neutral TGC interactions

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

$$L = \frac{-e}{M_Z^2}\left((h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})Z^\alpha\tilde{F}_{\rho\alpha} - \left(\frac{h_4^\gamma}{2M_Z^2}(\square\partial^\sigma F^{\rho\alpha}) + \frac{h_4^Z}{2M_Z^2}(\square + M_Z^2)\partial^\sigma Z^{\rho\alpha}\right)Z_\sigma\tilde{F}_{\rho\alpha}\right)$$

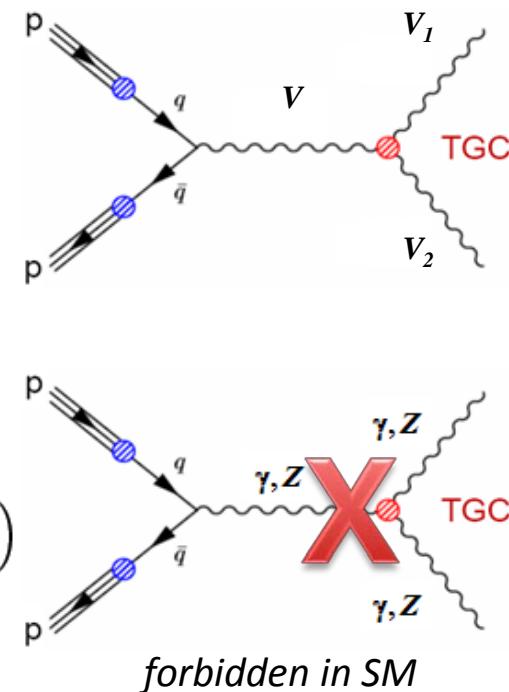
- Anomalous TGC effects:
enhancement in high p_T
changes in angular distributions

- Form factor to avoid unitarity violation

$$a = a_0 / (1 + \frac{\hat{s}}{\Lambda_{FF}^2})^n$$

Λ = cut-off scale
 n = FF power

- SM predictions: $\lambda_\gamma = \lambda_Z = 0$, $g^1_Z = \kappa_\gamma = \kappa_Z = 1$
- Neutral TGC ZZZ , $ZZ\gamma$, $Z\gamma\gamma$ are forbidden
(Z , γ has no charge nor weak isospin)



coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	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}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ



WWV aTGC in WW

$$L/g_{WWV} = ig_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + ik^V W_\mu^* W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2} W_{\rho\mu}^* W_\nu^\mu V^{\nu\rho}$$

Constraints to reduce number of aTGCs

→ LEP scenario

$$\Delta\kappa_\gamma = (\cos^2\theta_W / \sin^2\theta_W)(\Delta g_1^Z - \Delta\kappa_Z), \quad \lambda_Z = \lambda_\gamma$$

→ HISZ scenario

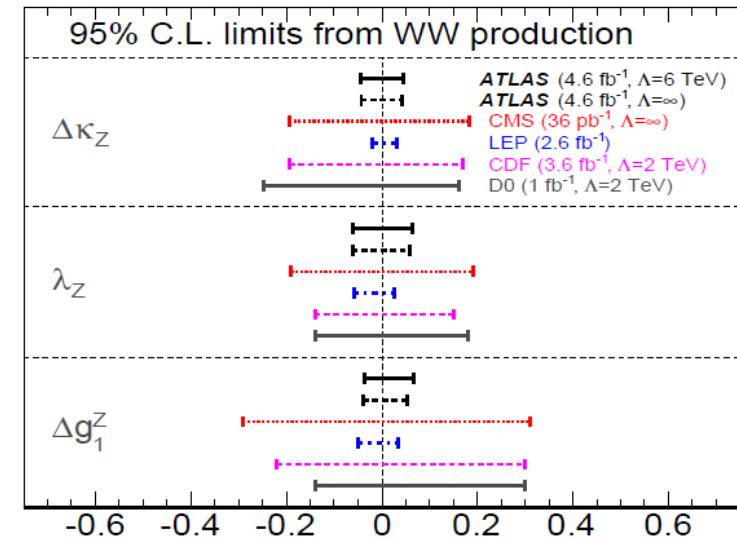
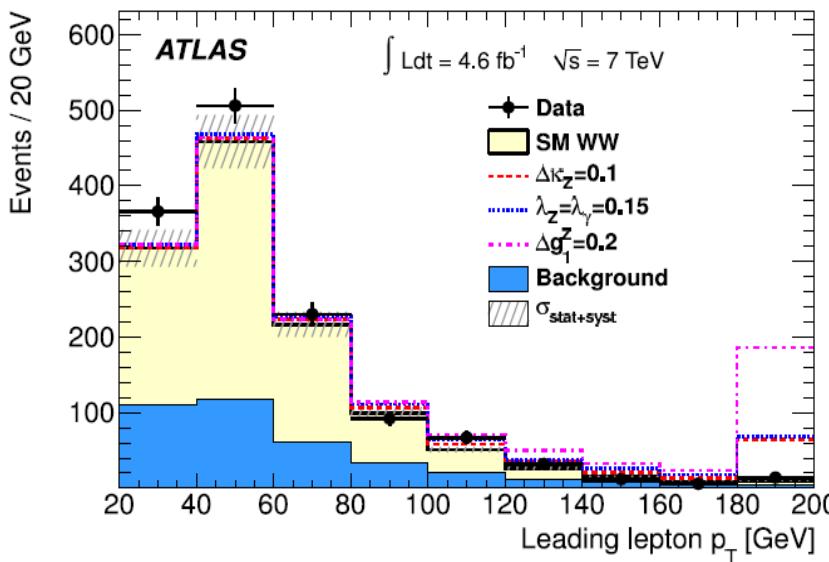
$$\Delta g_1^Z = \Delta\kappa_Z / (\cos^2\theta_W - \sin^2\theta_W), \quad \Delta\kappa_\gamma = 2\Delta\kappa_Z \cos^2\theta_W / (\cos^2\theta_W - \sin^2\theta_W), \quad \lambda_Z = \lambda_\gamma$$

→ Equal couplings

$$\Delta\kappa_Z = \Delta\kappa_\gamma, \quad \lambda_Z = \lambda_\gamma$$

Full 2011 dataset, likelihood for $p_T^\ell > 120$ GeV

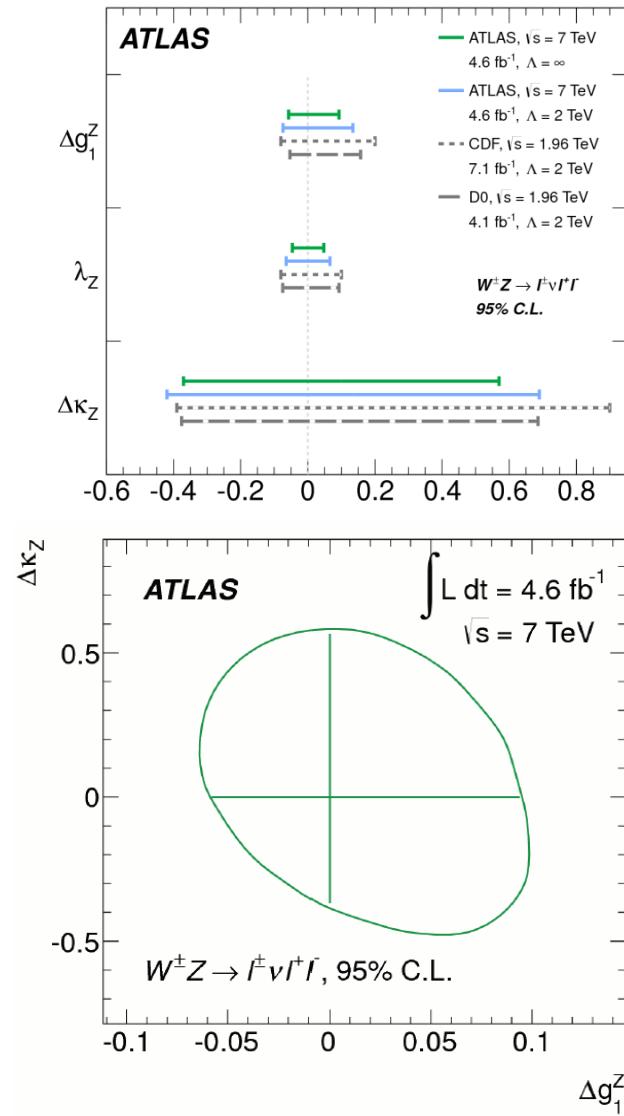
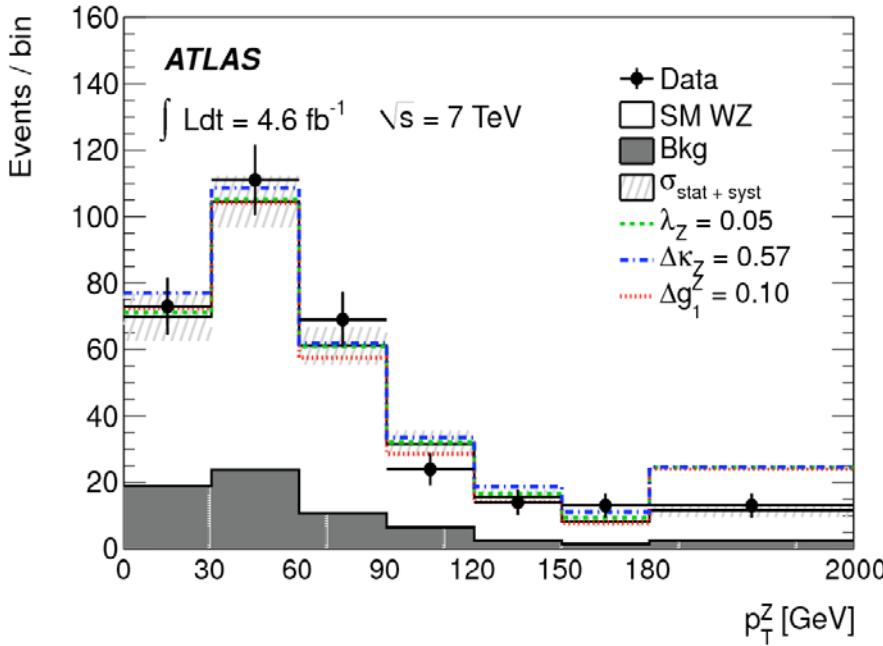
Consistent with SM predictions



WWZ aTGC in WZ

$$L/g_{WWV} = ig_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + ik^V W_\mu^* W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2} W_{\rho\mu}^* W_\nu^\mu V^{\nu\rho}$$

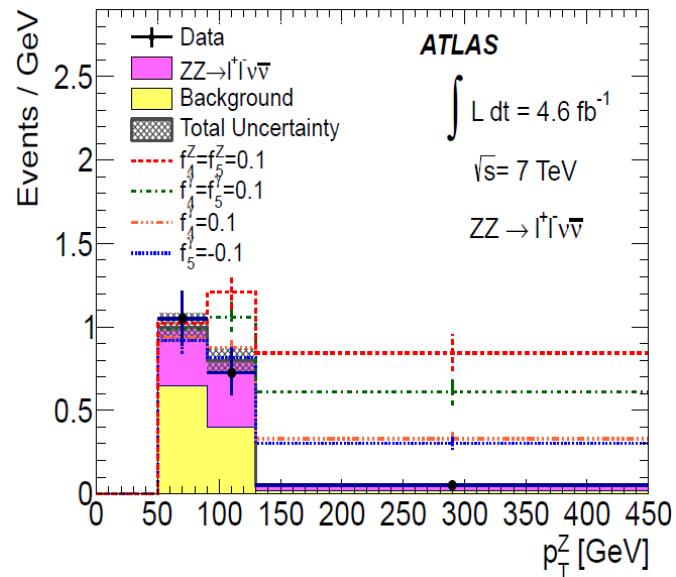
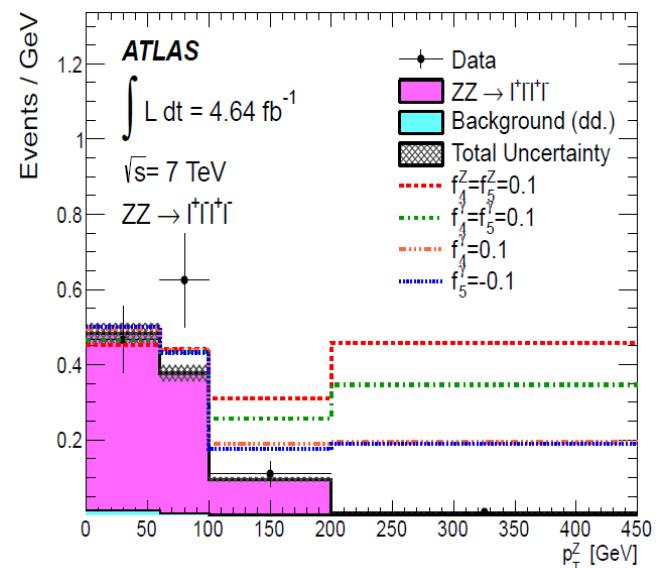
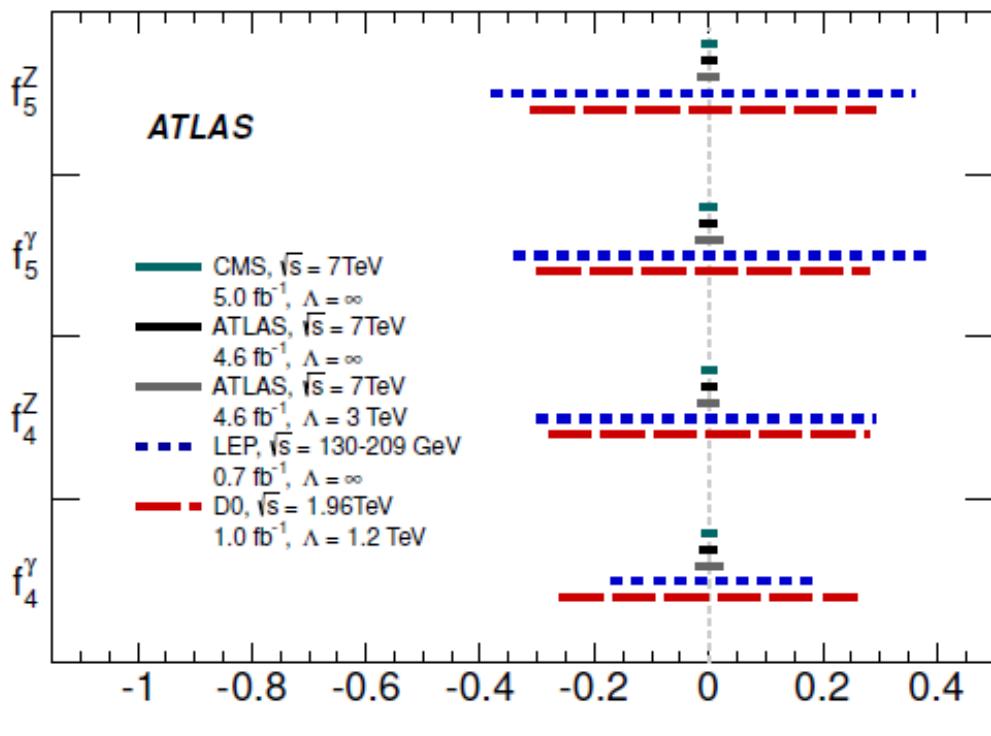
Full 2011 dataset
Consistent with SM predictions

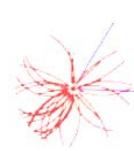


ZZV aTGC in ZZ

$$L = -\frac{e}{M_Z^2} [f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta]$$

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]



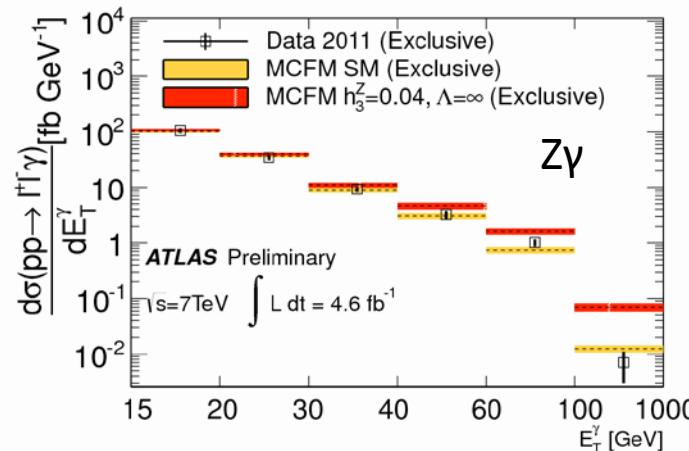
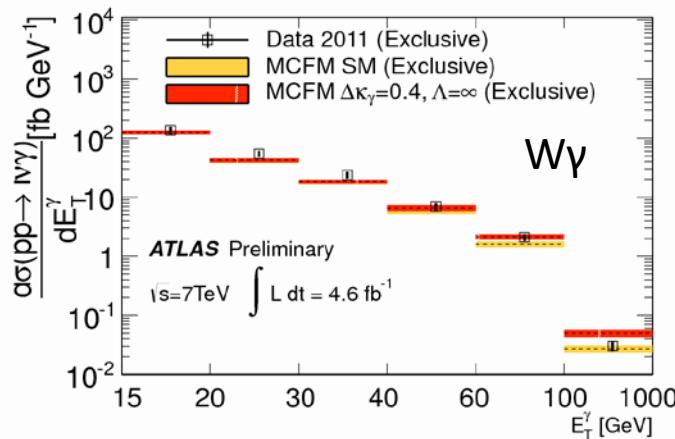


$WW\gamma$, $ZV\gamma$ aTGCs

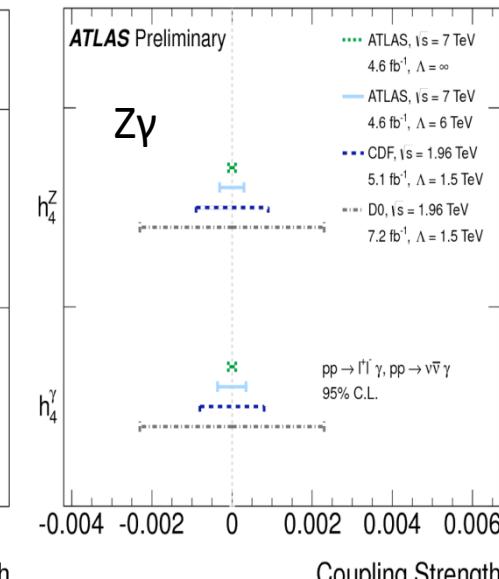
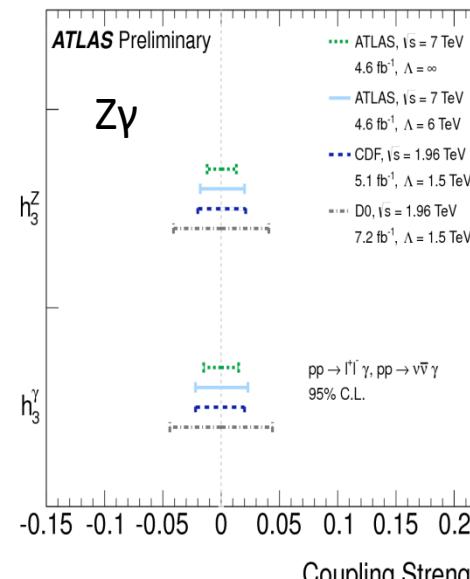
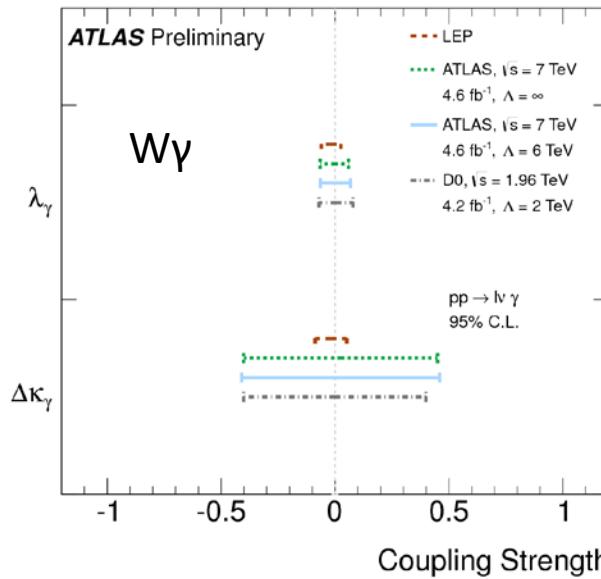
$$L/g_{WWV} = ig_1^V(W_{\mu\nu}^*W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + ik^V W_\mu^*W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2}W_{\rho\mu}^*W_\nu^\mu V^{\nu\rho}$$

$$L = \frac{-e}{M_Z^2} \left((h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho}) Z^\alpha \tilde{F}_{\rho\alpha} - \left(\frac{h_4^\gamma}{2M_Z^2} (\square \partial^\sigma F^{\rho\alpha}) + \frac{h_4^Z}{2M_Z^2} (\square + M_Z^2) \partial^\sigma Z^{\rho\alpha} \right) Z_\sigma \tilde{F}_{\rho\alpha} \right)$$

aTGCs tests on photon E_T distributions, hard-jet veto



aTGCs, no deviation to SM predictions





Summary

- Measurements of diboson production in **WW, WZ, ZZ, Wγ, Zγ** have been performed
- Production cross sections are in agreement with the Standard Model predictions
- Contributions of Anomalous Triple Gauge Couplings, not observed, limits are set
- Update analyses with full 8 TeV data expected soon ..