Diboson Production Cross Section @ LHC

On behalf of the ATLAS and CMS Collaborations

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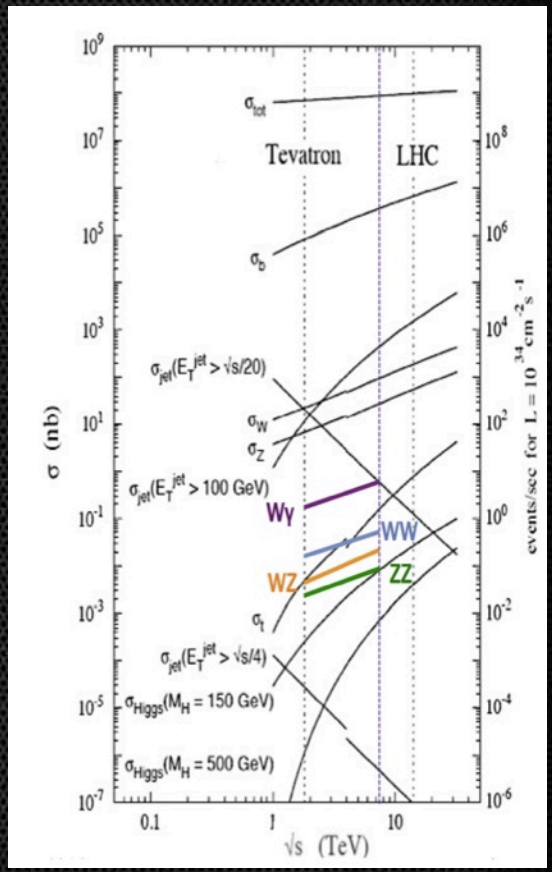
Diboson Physics

- Diboson production cross-section measurements
  - Test of SM electroweak theory and perturbative QCD at TeV scale
  - Irreducible SM background to Higgs (WW, ZZ, Zγ)
  - Sensitivity to new particles decaying to dibosons (Technicolor, Little Higgs, SUSY, etc…)
  - Small cross sections O(1-100 pb)
- Anomalous Triple Gauge Couplings (aTGC)
  - aTGC modify total cross sections and kinematics
  - neutral TGC not allowed in the SM (ZZZ, ZZγ)
  - an effective Lagrangian featuring such couplings can be constructed and tested

s-channel TGC vertex

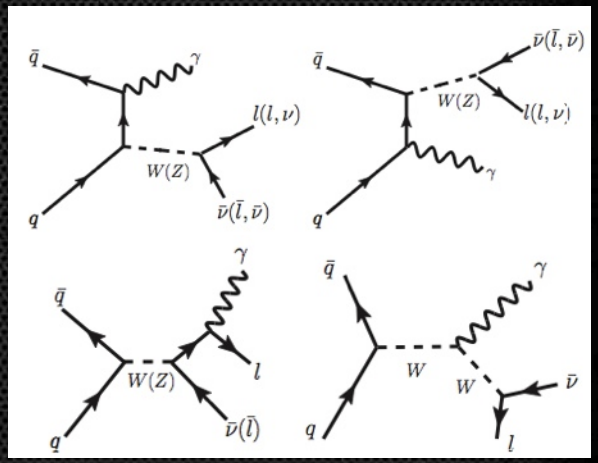


W(lν)γ, Z(ll)γ Cross Sections

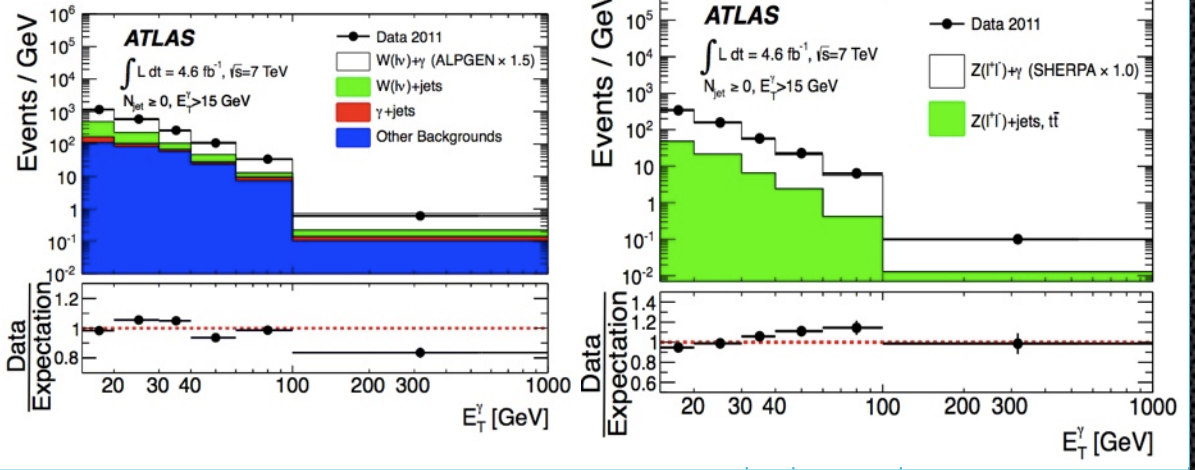
Selection highlights *

- at least one isolated photon $E_T^{\gamma} > 15$ GeV
- $\Delta R(l, \gamma) > 0.7$ to suppress FSR photons
- $E_T^{miss} > 35$ GeV (Wγ channel)

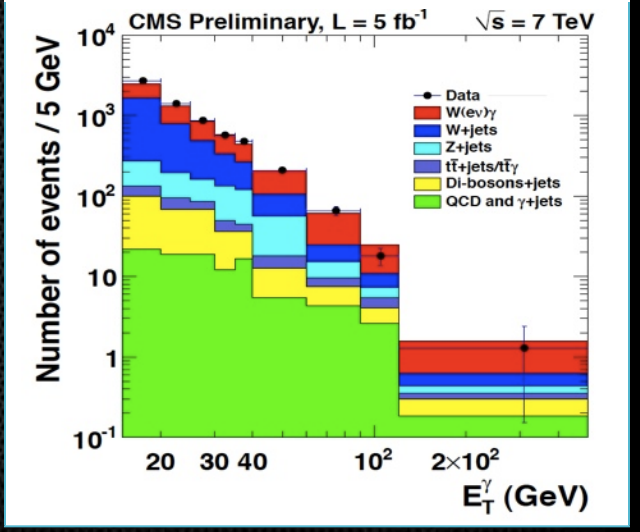
* ATLAS cuts shown (CMS cuts are similar)



ATLAS *7 TeV* *4.6 fb^{-1}* *arXiv: 1302.1283 (submitted to PRD)*



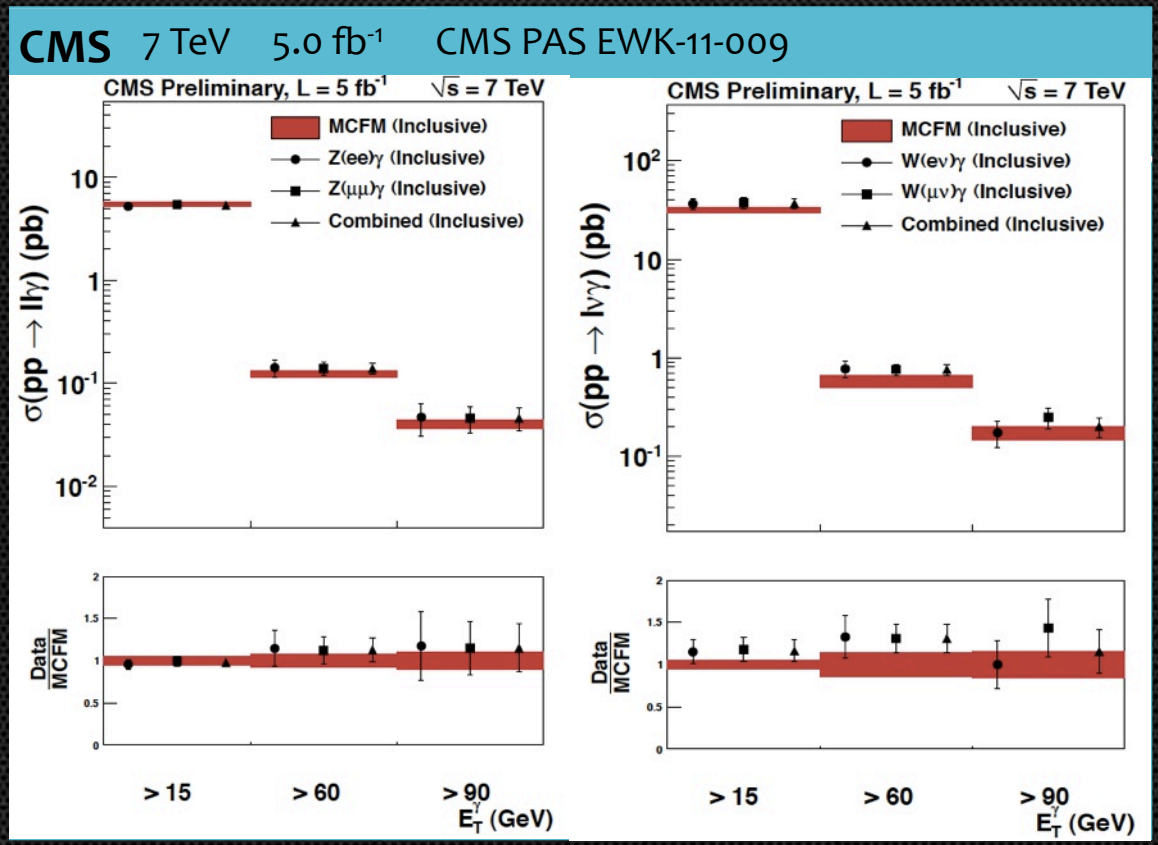
CMS *7 TeV* *5.0 fb^{-1}* CMS PAS EWK-11-009



- Backgrounds: W/Z + jets (dominant)

W(lν)γ, Z(ll)γ Cross Sections

- Unfolding the E_T^γ spectrum

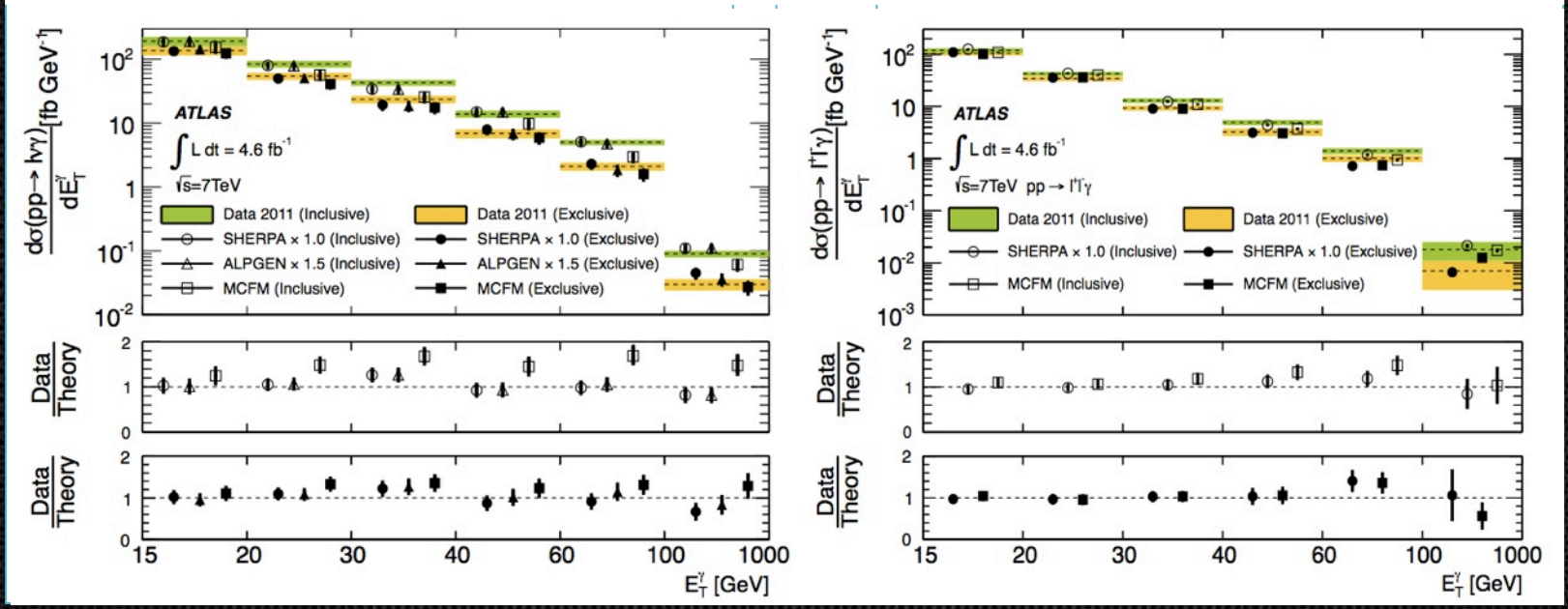


- Zγ: good agreement with MCFM predictions
- Wγ: fair agreement with MCFM (at the one sigma level)

W(lν)γ, Z(ll)γ Cross Sections

- Unfolding the E_T^γ spectrum

ATLAS *7 TeV 4.6 fb^{-1} arXiv: 1302.1283 (submitted to PRD)*



- Wγ: the shape is well reproduced by ALPGEN/SHERPA
- Wγ: MCFM NLO shows discrepancies in the high-E_T^γ spectrum
- Zγ: good agreement with SHERPA and MCFM NLO predictions

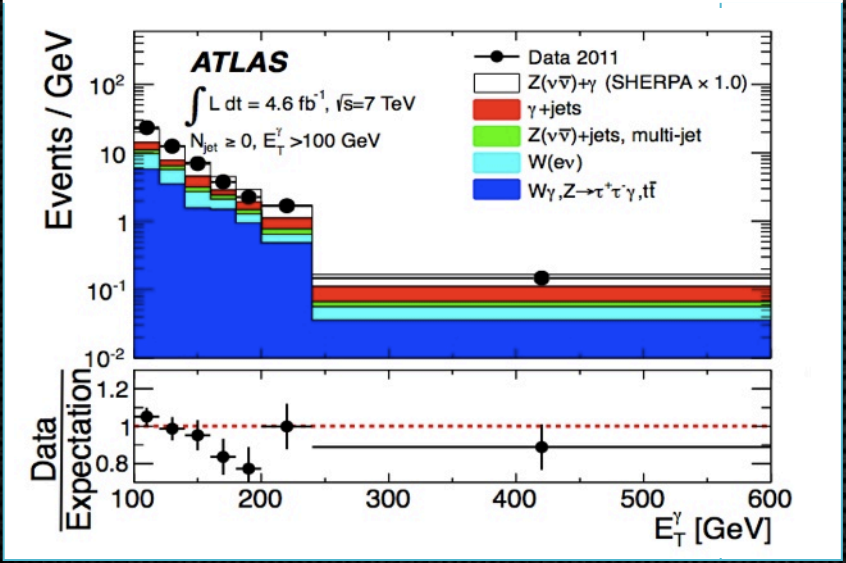
Z(νν) γ Cross Section

Selection highlights *

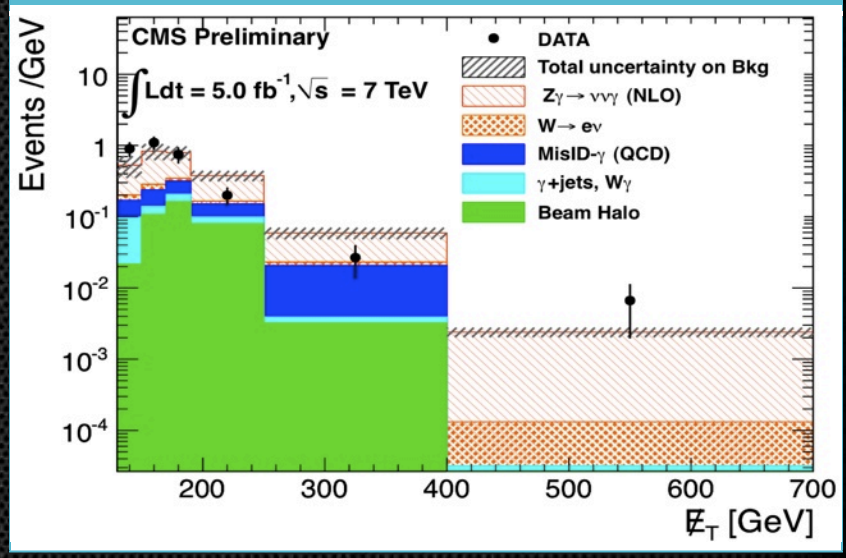
- one isolated photon $E_T^{\gamma} > 100$ GeV
- $E_T^{miss} > 90$ GeV
- well separated $\Delta\phi(E_T^{miss}, \text{jet})$ & $\Delta\phi(E_T^{miss}, \gamma)$
- high-pT lepton veto

* ATLAS cuts shown (CMS $E_T^{\gamma} > 145$ GeV)

ATLAS *7 TeV 4.6 fb^{-1} arXiv: 1302.1283*



CMS *7 TeV 5.0 fb^{-1} CMS SMP-12-020*



- Backgrounds: Wγ, W(eν), γ+jets, multi-jets

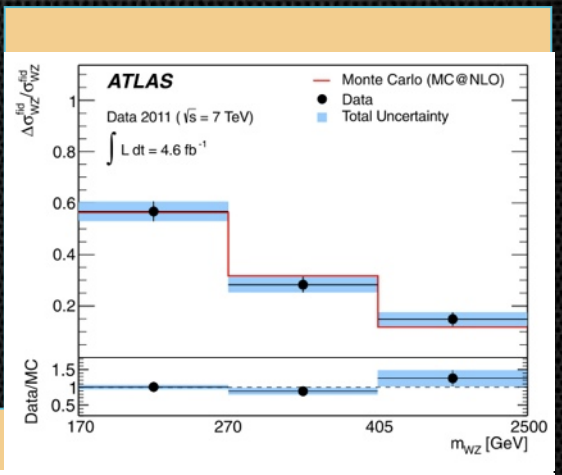
Fair agreement with theoretical predictions

WZ→3lν Cross Section

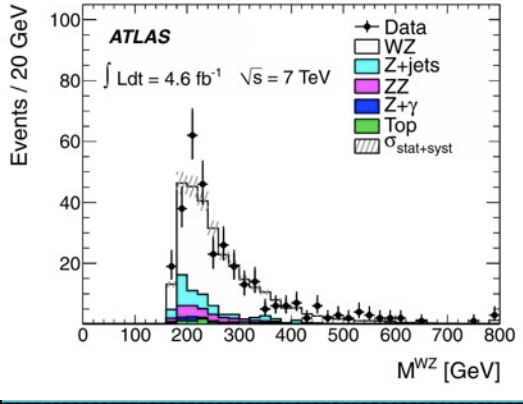
Selection highlights *

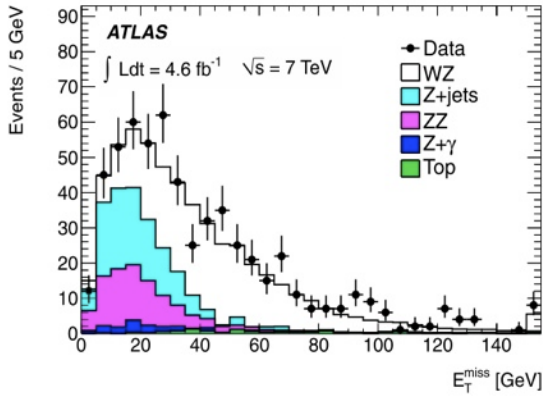
- exactly 3 isolated high-p_T leptons
- E_T^{miss} > 25 GeV
- tight Z mass window cut (10 GeV)
- lepton from W: tighter ID/isolation

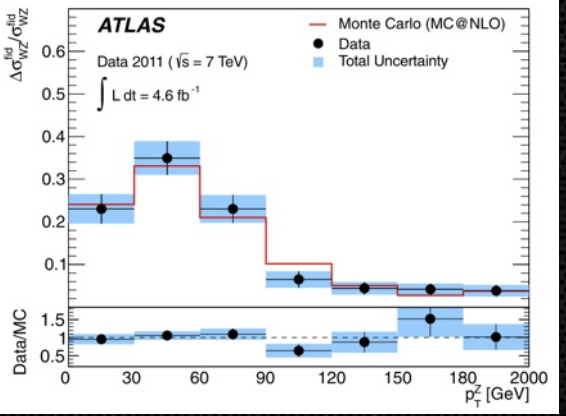
* ATLAS cuts



ATLAS *7 TeV* *4.6 fb⁻¹* *EPJ C (2012) 72:2173*





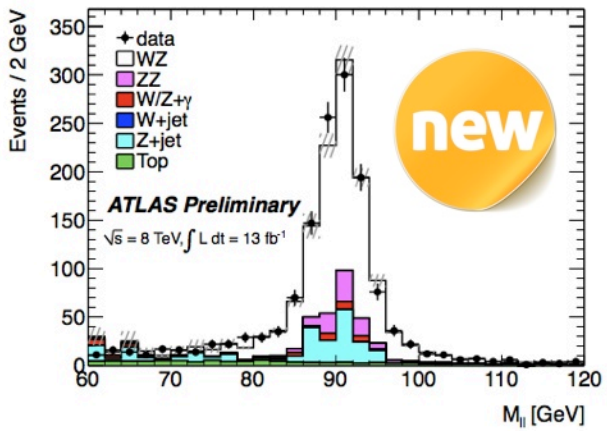


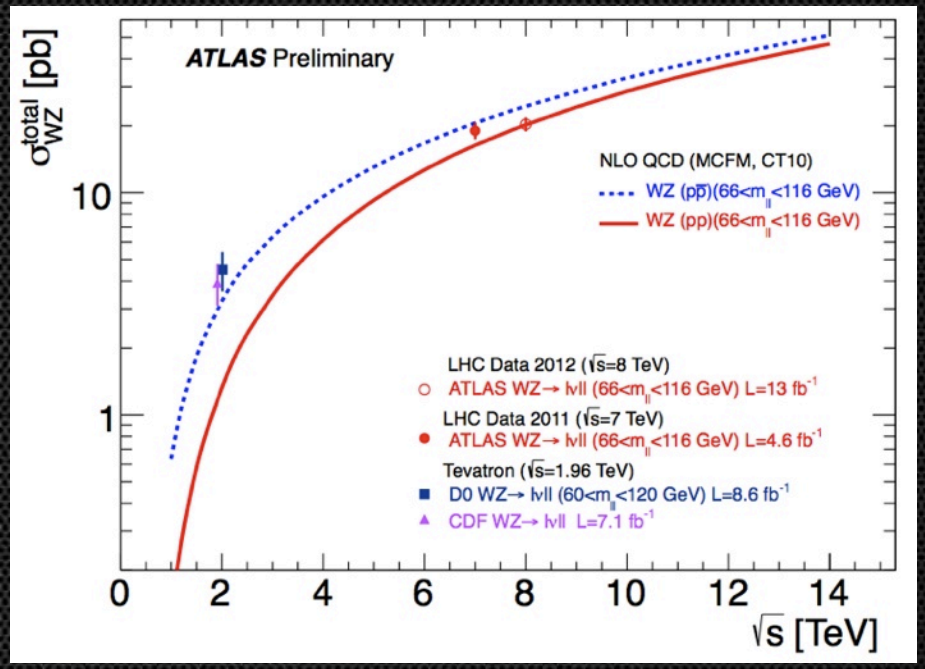
- Backgrounds: Z + jets, ZZ, Zγ, top-quark

WZ Cross Section

ATLAS: WZ→3lν analysis @ 8 TeV with 13 fb^{-1}

ATLAS 8 TeV 13 fb^{-1} ATLAS-CONF-2013-021





fb^{-1}	σ(pp →WZ + X) [pb]
ATLAS 7TeV	4.6	$19.0^{+1.4}_{-1.3}(stat) \pm 0.9(syst) \pm 0.4(lumi)$
CMS 7TeV	1.1	$17.0 \pm 2.4(stat) \pm 1.1(syst) \pm 1.0(lumi)$
ATLAS 8TeV	13	$20.3^{+0.8}_{-0.7}(stat)^{+1.2}_{-1.1}(syst)^{+0.7}_{-0.6}(lumi)$

- MCFM NLO + CT10 prediction: 20.3 ±0.8 pb (excellent agreement)

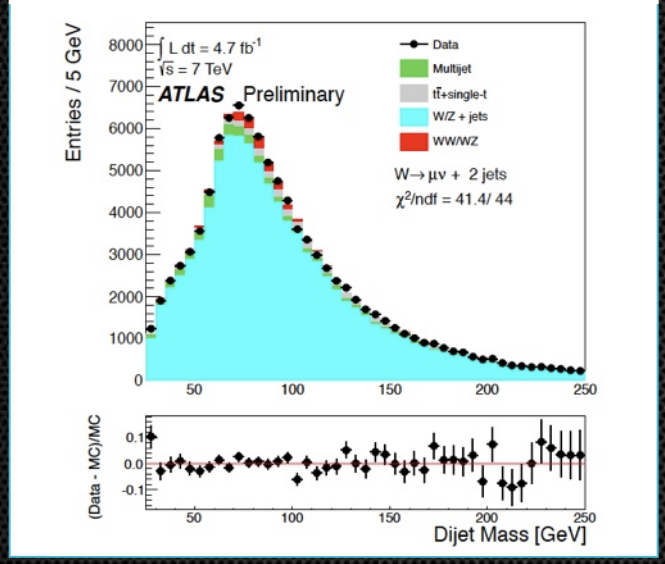
(WZ+WW)→jjlν Cross Section

Selection highlights * (electron)

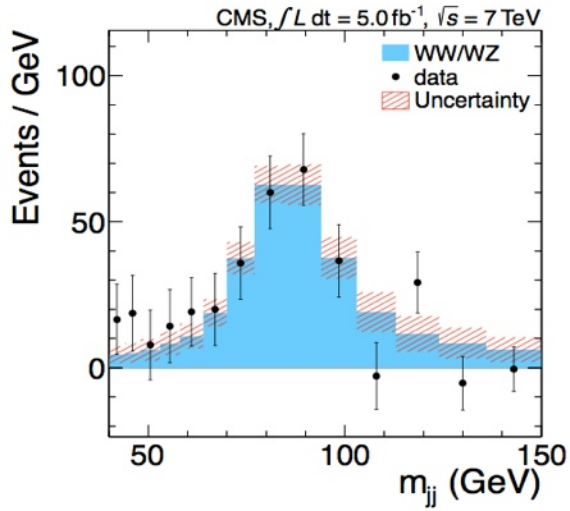
- exactly one lepton with $p_T > 25$ (35) GeV)
- exactly two jets with $p_T > 35$ GeV
- $E_T^{miss} > 25$ (30) GeV

* CMS cuts shown (ATLAS cuts are quite similar)

ATLAS *7 TeV 4.7 fb^{-1} ATLAS-CONF-2012-157*



CMS *7 TeV 5.0 fb^{-1} Eur. Phys .J C73 (2013) 2283*



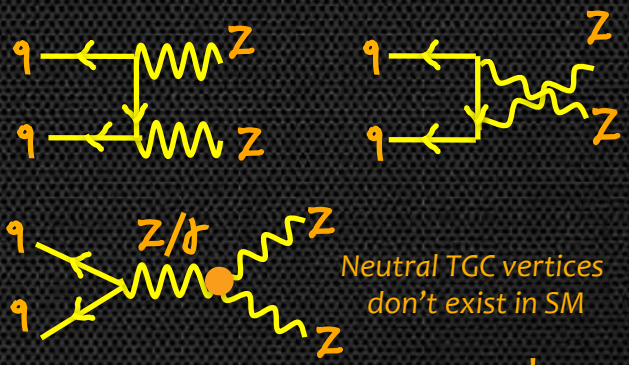
	fb^{-1}	σ(pp → WZ+ZZ) [pb]
ATLAS	4.7	$72 \pm 9(stat) \pm 15(syst) \pm 13(MC\ stat)$
CMS	5.0	$68.9 \pm 8.7(stat) \pm 9.7(syst) \pm 1.5(lumi)$
Theory		63.4 ± 2.6

- Backgrounds: W/Z+jets (dominant)
- Signal: from binned ML fit to m_{jj} (ATLAS/CMS)

ZZ→4l Cross Section

Selection highlights

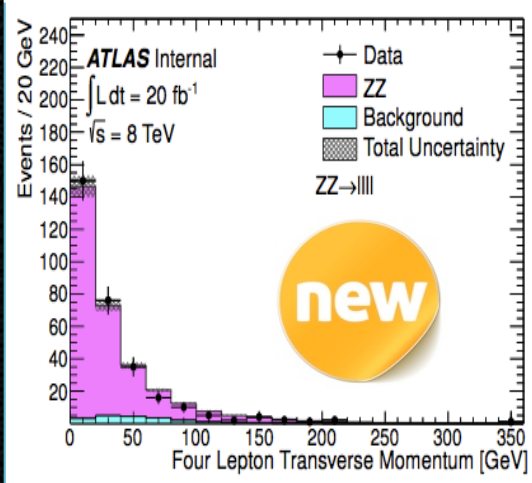
- 4 isolated high-p_T leptons
- require both Z bosons on shell

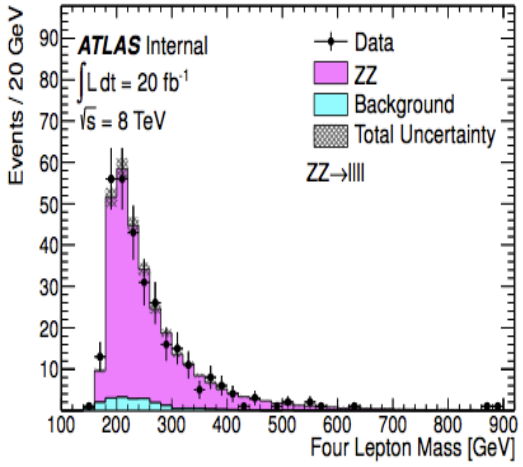


gluon fusion 6%

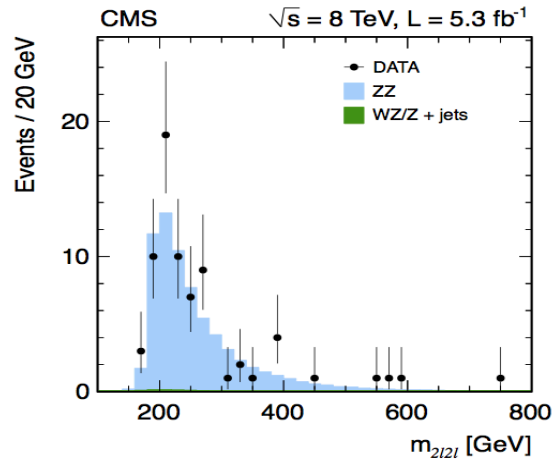
ATLAS update: ZZ→4l analysis @ 8 TeV with 20 fb^{-1}

ATLAS *8 TeV* *20 fb^{-1}* ATLAS-CONF-2013-020





CMS 8 TeV 5.3 fb^{-1} arXiv: 1301.4698
submitted to PLB



- Backgrounds: very clean signature

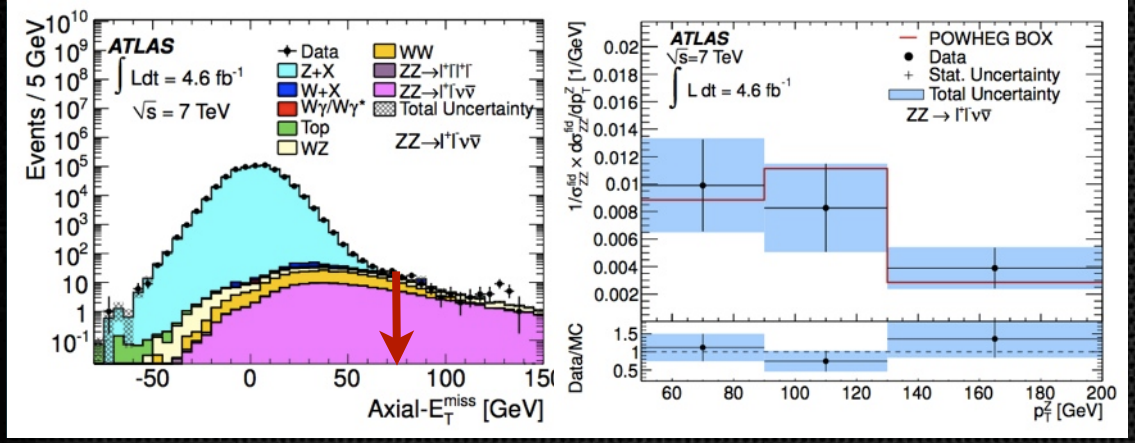
ZZ→2l2τ, 2l2ν Cross Sections

ATLAS analysis @ 7 TeV includes ZZ →2l 2ν

Selection highlights

- 2 isolated high-p_T leptons (same flavor/opp. sign)
- axial-E_T^{miss} > 75 GeV to reduce Z+jets
- jet veto to suppress top-quark background

ATLAS *7 TeV* *4.6 fb^{-1}* arXiv: 1211.6096 (submitted to JHEP)



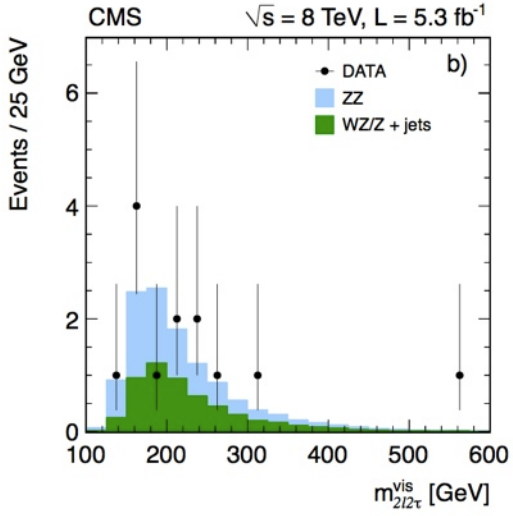
- axial-E_T^{miss}: projection of the E_T^{miss} along the direction opposite to Z->ll in the transverse plane

CMS analysis @ 8 TeV includes ZZ →2l 2τ

Selection highlights

- 4 channels: $\tau_h\tau_h, \tau_h\tau_e, \tau_h\tau_\mu, \tau_e\tau_\mu$
- visible inv. mass 30 < $m_{2\tau}$ < 90 GeV

CMS 8 TeV 5.3 fb^{-1} arXiv: 1301.4698
submitted to PLB

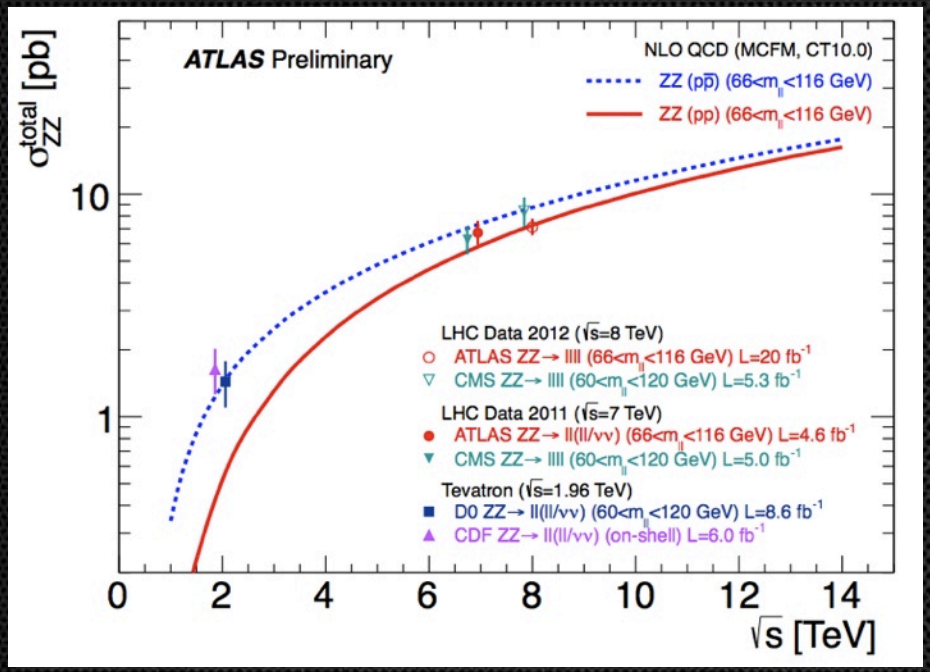


ZZ Cross Section

	fb^{-1}	$\sigma(pp \rightarrow ZZ + X)$ [pb]
ATLAS 7TeV	4.6	$6.7 \pm 0.7(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi)$
CMS 7TeV	5.0	$6.2^{+0.9}_{-0.8}(stat)^{+0.4}_{-0.3}(syst) \pm 0.1(lumi)$
ATLAS 8TeV	20	$7.1^{+0.5}_{-0.4}(stat) \pm 0.3(syst) \pm 0.2(lumi)$
CMS 8TeV	5.3	$8.4 \pm 1.0(stat) \pm 0.7(syst) \pm 0.4(lumi)$

MCFM NLO + CT10 prediction

@ 8 TeV: $7.2^{+0.3}_{-0.2}$ pb



- Good agreement ATLAS/CMS
- Comparison with MCFM NLO + CT10 shows a good agreement
- Still limited by statistics
- Main syst: lepton reco/ID/isolation

CMS 7 TeV ZZ: JHEP 1301 (2013) 063

ATLAS 7 TeV ZZ: arXiv: 1211.6096 (differential cross sections are also available in the 4l channel)

WW→lνlν Cross Section

Selection highlights *

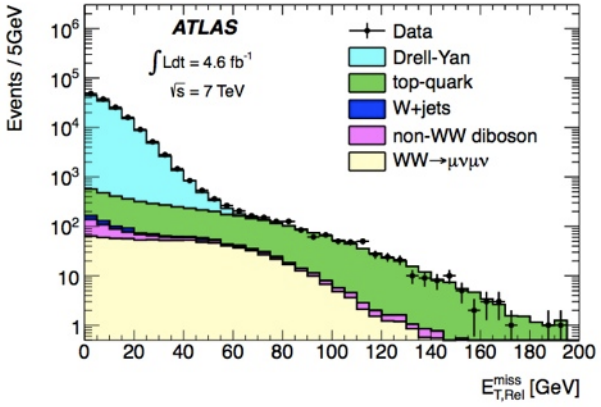
$$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \times \sin(\Delta\phi) & \text{if } \Delta\phi < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

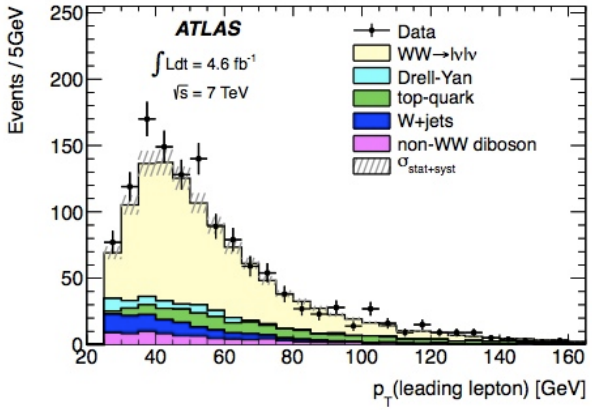
- two isolated high-p_T leptons (opposite sign)
- Z veto to suppress Drell-Yan $|m_{ll}-m_Z| > 15$ GeV (ee,μμ)
- $E_{T,Rel}^{miss} > 45$ GeV (ee, μμ) and > 25 GeV (eμ)
- jet veto to suppress the top background

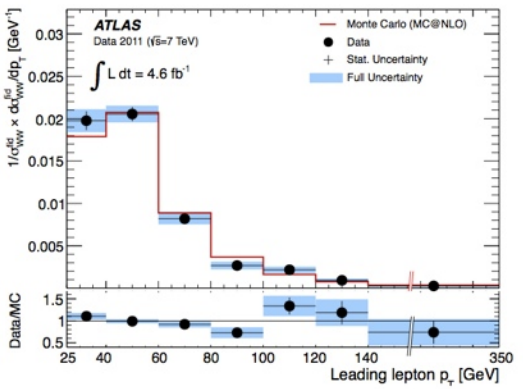
SM LO diagrams

* ATLAS cuts shown (CMS cuts are similar)

ATLAS *7 TeV* *4.6 fb^{-1}* *arXiv: 1210.2979 (submitted to PRD)*



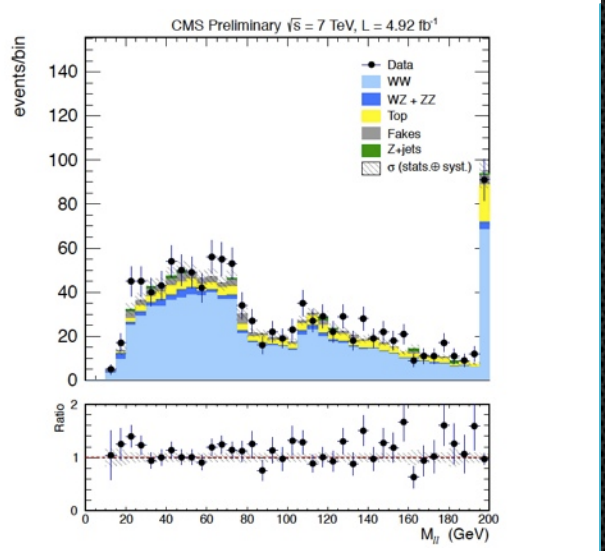




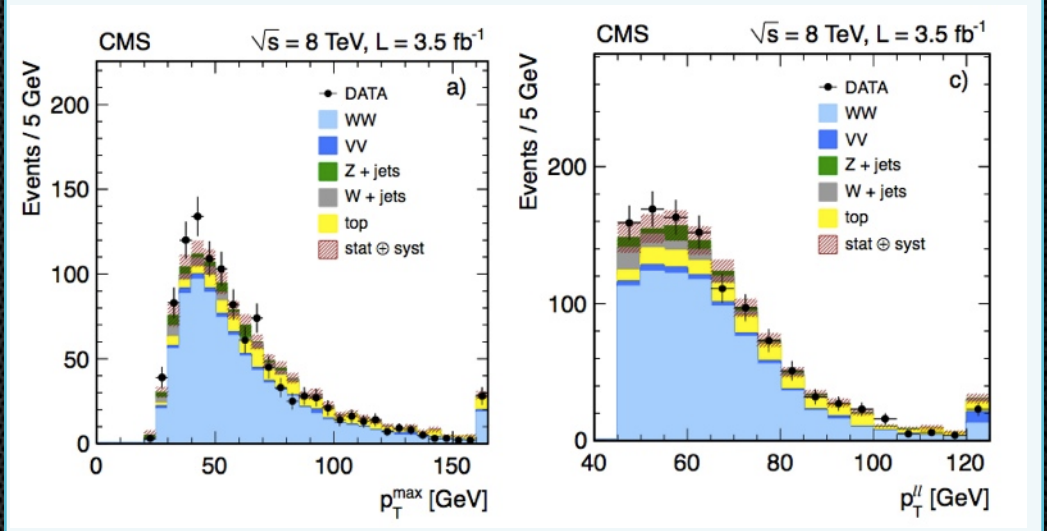
- Higgs to WW increases the WW production by 3%

WW→lνlν Cross Section

CMS 7 TeV *4.9 fb^{-1}* CMS PAS SMP-12-005



CMS 8 TeV 3.5 fb^{-1} arXiv: 1301.4698 (submitted to PLB)



- jeto veto efficiency is the main source of systematics (for both CMS and ATLAS)

		fb^{-1}	σ(pp →WW + X) [pb]	SM NLO
ATLAS	7TeV	4.6	$51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 2.0(lumi)$	$44.7^{+2.1}_{-1.9}$
CMS	7TeV	4.9	$52.4 \pm 2.0(stat) \pm 4.5(syst) \pm 1.2(lumi)$	–
CMS	8TeV	3.5	$69.9 \pm 2.8(stat) \pm 5.6(syst) \pm 3.1(lumi)$	$57.3^{+2.4}_{-1.6}$

MCFM NLO+CT10

CMS 7 TeV WW: CMS PAS SMP-12-005 ATLAS 7 TeV WW: arXiv: 1211.6096

aTGC - ZZV

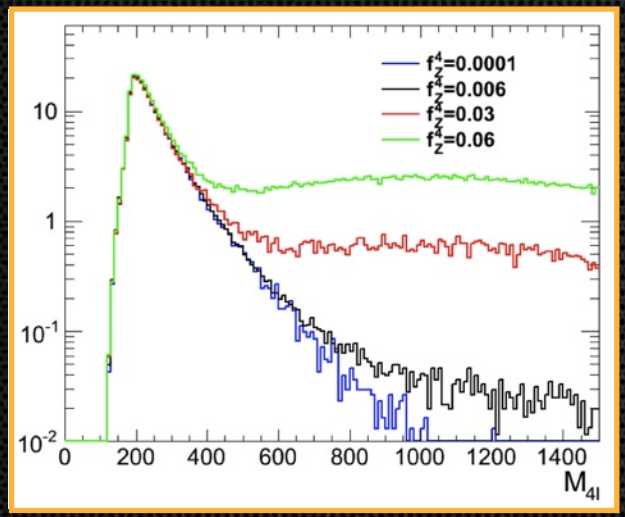
s-channel TGC vertex

- aTGC modelled using an effective Lagrangian depending on few parameters

In SM all **parameters** = 0

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

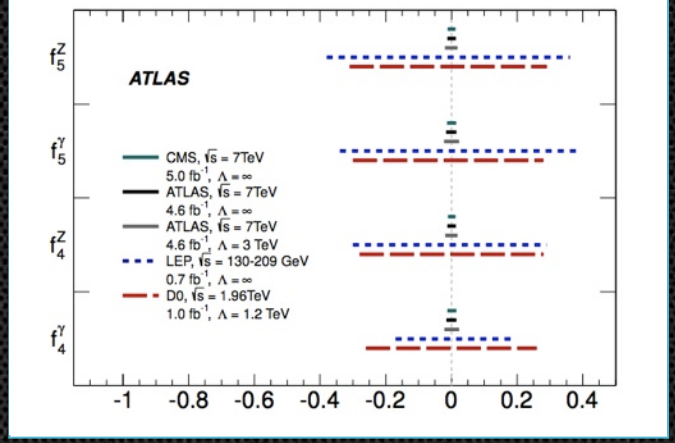
- aTGC sensitivity to $M^{VV'}$, p_T^V, etc...
- likelihood test incorporating:
  - excpected signal as function of the aTGCs
  - backgrounds, sytematics as nuisance parameters



CMS 7 TeV ZZ: JHEP 1301 (2013) 063
ATLAS 7 TeV ZZ: arXiv: 1211.6096

ZZV (V =Z, γ) via ZZ production

ATLAS/CMS *7 TeV* *4.6 - 5.0 fb^{-1}*

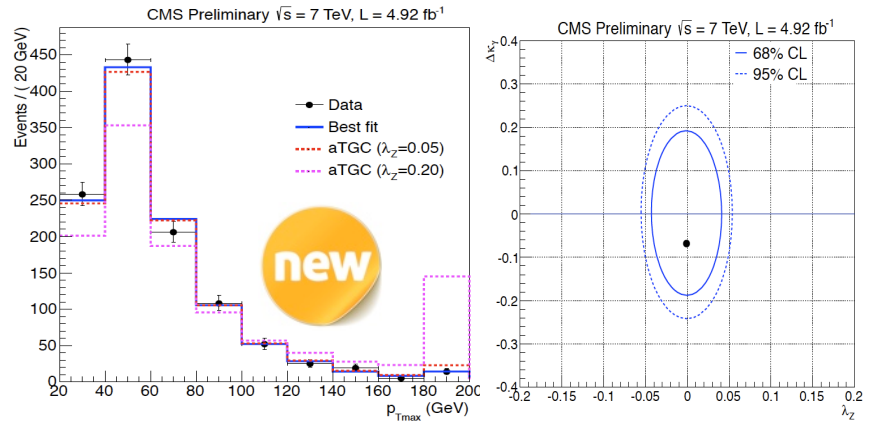


No deviations from SM observed

aTGC -WWV

WWV (V =Z, γ) via WW, WZ, Wγ production

CMS 7 TeV *4.9 fb^{-1}* CMS PAS SMP-12-005

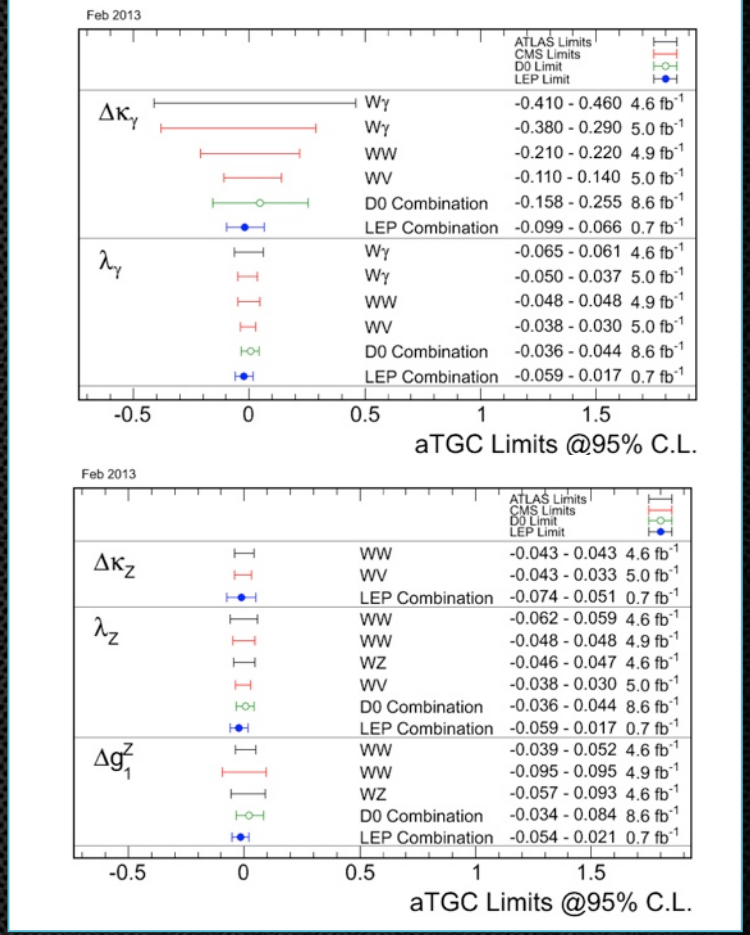


CMS results on aTGC in WW @ 7 TeV

- using the leading lepton p_T distribution
- aTGC also measured in WW/WZ→jjlν

No deviations from SM observed

ATLAS/CMS 7 TeV WW ,WZ, Wγ

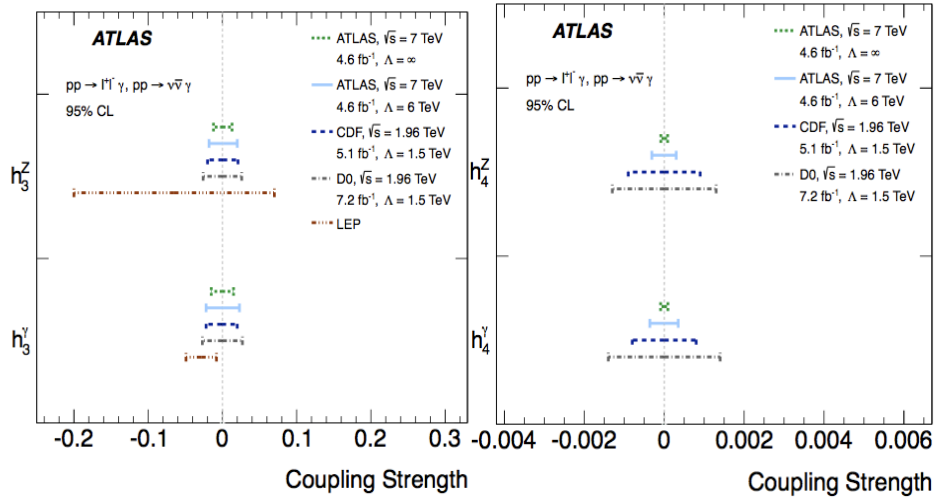


ATLAS 7 TeV Wγ: arXiv:1302.1283, ATLAS 7 TeV WZ: EPJ C72 (2012) 2173
CMS 7 TeV Wγ : CMS EWK-11-009, CMS 7 TeV WW: CMS SMP-12-005, CMS 7 TeV VW (V=W,Z jj): EPJ C73 (2013) 2283

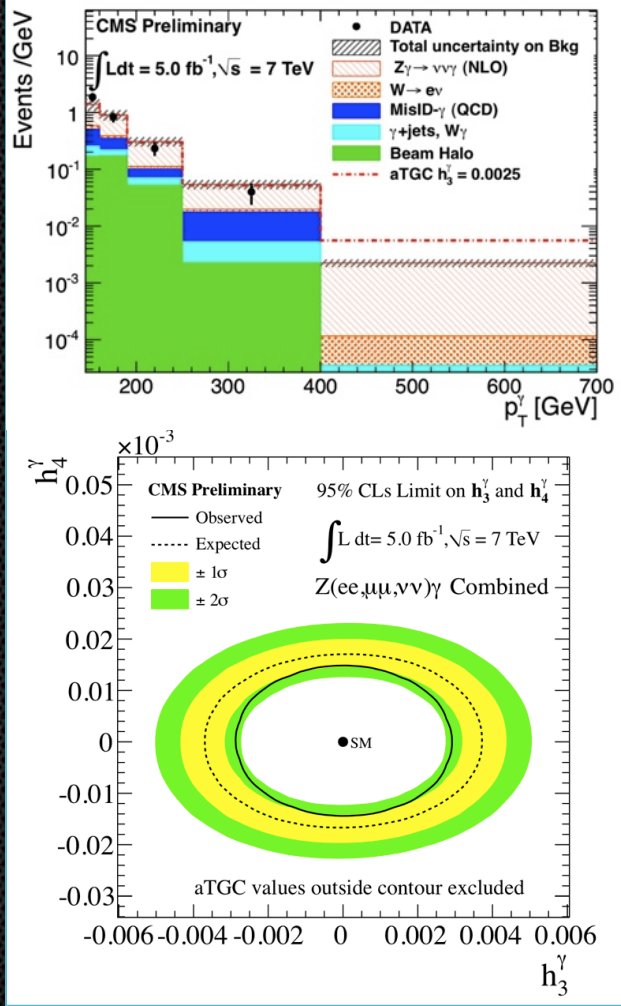
aTGC - ZVγ

ZVγ (V = Z, γ) via Zγ production

ATLAS *7 TeV* *4.6 fb^{-1}* *arXiv: 1302.1283*



CMS *7 TeV* *5.0 fb^{-1}* CMS SMP-12-020



aTGC measured in Zγ (eeγ, μμγ & ννγ)

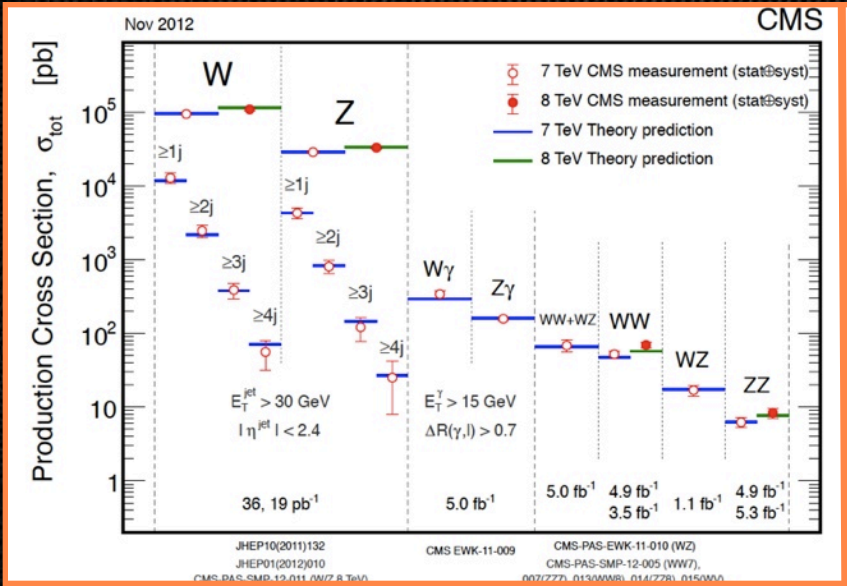
- ννγ dominates the sensitivity in CMS

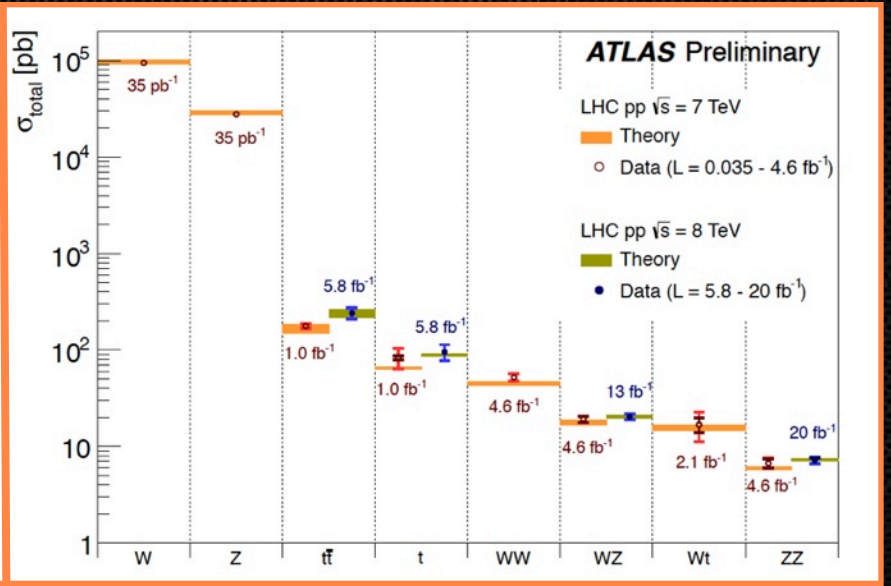
No deviations from SM observed

ATLAS 7 TeV Zγ: arXiv:1302.1283 CMS 7 TeV Zγ : CMS EWK-11-009 / CMS SMP-12-020

Conclusions

- Excellent performance of the LHC
  - ~5 fb^{-1} @ 7 TeV, ~ 20 fb^{-1} @ 8 TeV (per experiment)
- Diboson Cross-section measurements match NLO SM predictions





- aTGC measurements show no apparent deviation from SM
  - limitations due to statistics, still to be analysed the full 8 TeV dataset
  - sensitivity is expected to increase with centre-of-mass energy

Backup

Cross Section Measurements

- Count observed events after selection requirements
- Background estimation using data-driven and MC-based methods
- Measure the fiducial cross-section (within detector acceptance)
- Measure the total cross-section (extrapolated to full/extended phase space)

Fiducial x-section	Total x-section
$\sigma_{fid} = \frac{N_{obs} - N_{bkg}}{C \cdot L}$	$\sigma_{tot} = \frac{\sigma_{fid}}{A \cdot Br}$
N_{obs} = events passing selection N_{bkg} = estimated backgrounds	
C = efficiency correction A = acceptance correction	
L = integrated luminosity Br = branching ratio of sub-decay	

- **C** adjusted to data/MC differences
  - lepton reco/ID
  - energy scale/resolution
  - trigger efficiency
  - etc...
- **A** based on MC tools
  - ME, parton shower, PDFs, etc..

- Measure differential cross sections as function of M^{VV}, p_T^V, etc...
  - using bin-by-bin correction factors or advanced unfolding techniques

Wγ, Zγ

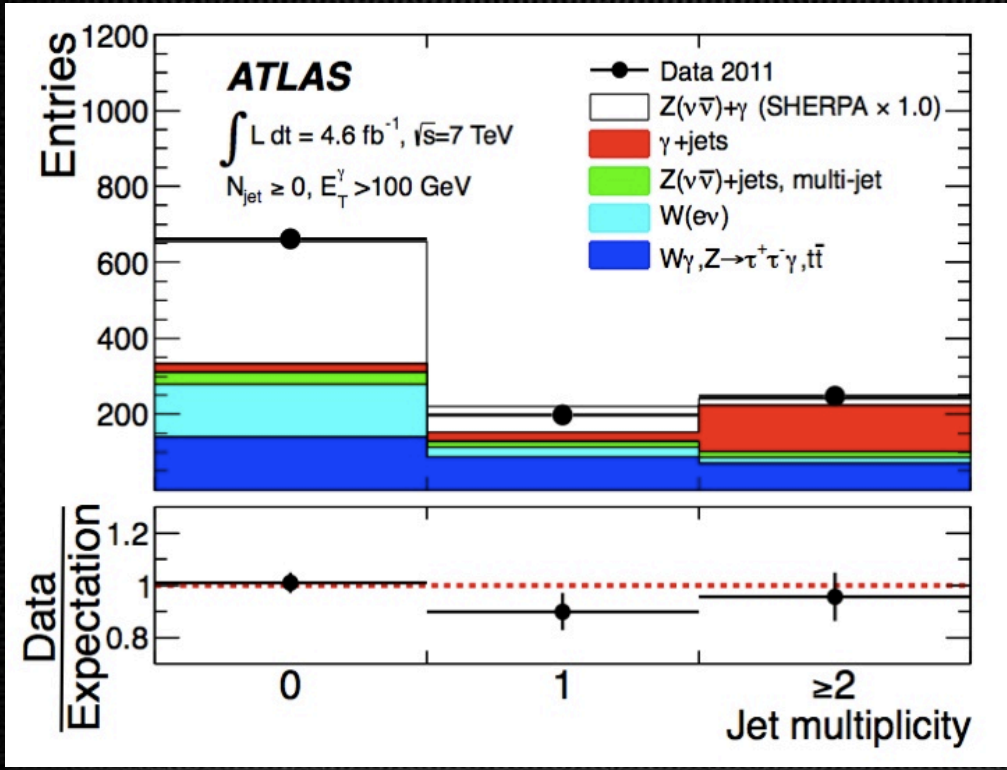
Systematic uncertainties on efficiency: $C_{V\gamma}$

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 acceptance: $A_{V\gamma}$

- PDF: ~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: ~0.5% obtained by varying ×2 around their nominal value

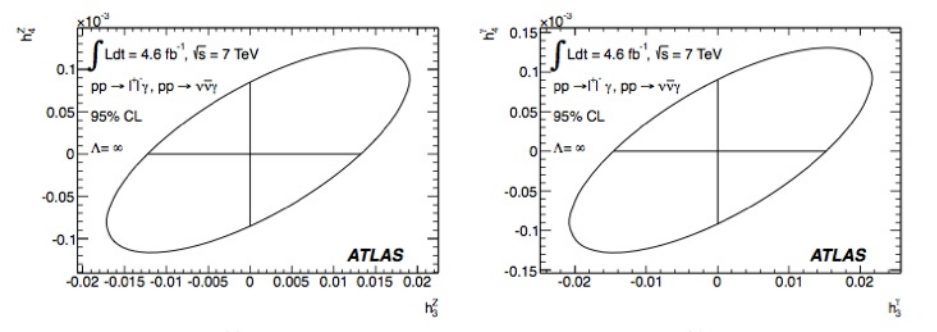
Wγ, Zγ



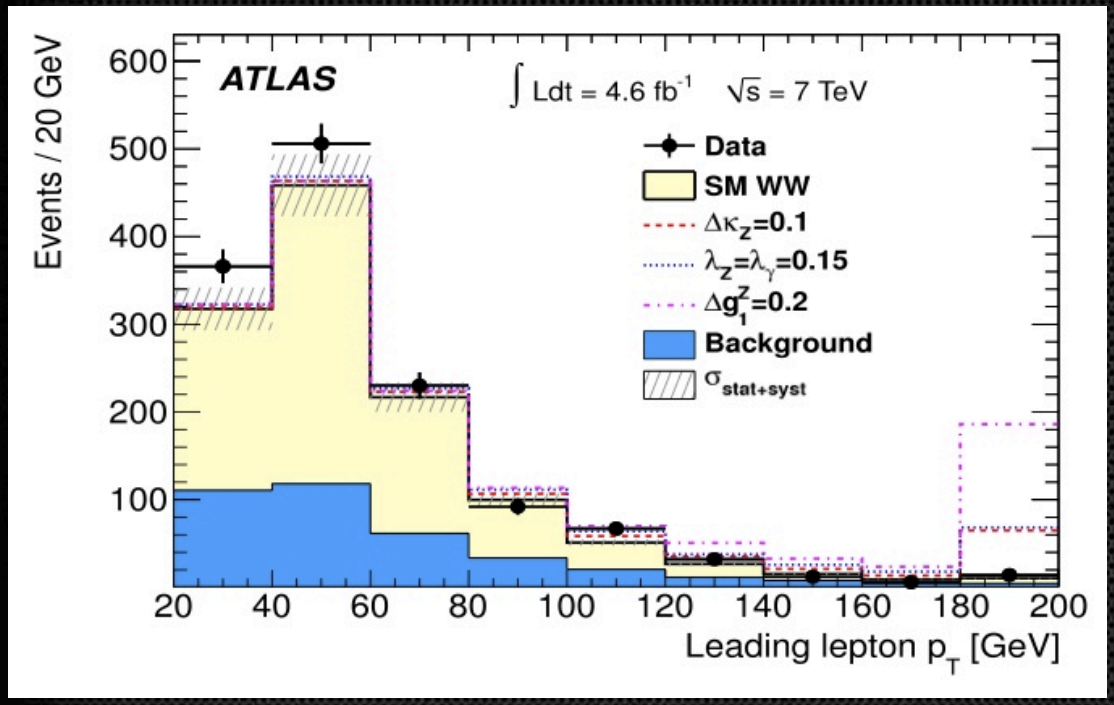
	$\nu\bar{\nu}\gamma$ $N_{\text{jet}} \geq 0$	$\nu\bar{\nu}\gamma$ $N_{\text{jet}} = 0$
$N_{Z\gamma}^{\text{obs}}$	1094	662
$W(e\nu)$	$171 \pm 2 \pm 17$	$132 \pm 2 \pm 13$
$Z(\nu\bar{\nu})$+jets, multi-jet	$70 \pm 13 \pm 14$	$29 \pm 5 \pm 3$
$W\gamma$	$238 \pm 12 \pm 37$	$104 \pm 9 \pm 24$
γ+jets	$168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

Wγ, Zγ

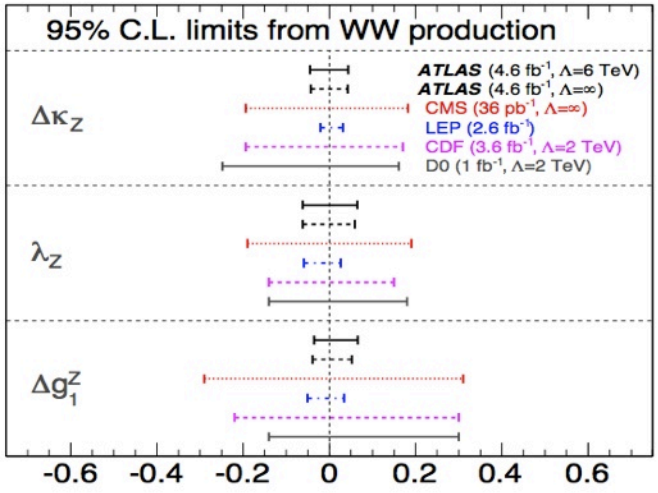
	Measured	Expected
processes	$pp \to \ell\nu\gamma$	
Λ	∞	∞
$\Delta\kappa_\gamma$	$(-0.41, 0.46)$	$(-0.38, 0.43)$
λ_γ	$(-0.065, 0.061)$	$(-0.060, 0.056)$
Λ	6 TeV	6 TeV
$\Delta\kappa_\gamma$	$(-0.41, 0.47)$	$(-0.38, 0.43)$
λ_γ	$(-0.068, 0.063)$	$(-0.063, 0.059)$
processes	$pp \to \nu\nu\gamma$ and $pp \to \ell^+\ell^-\gamma$	
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



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	$[-0.449, 0.546]$	$[-0.373, 0.562]$
$\Delta\kappa_\gamma$	$[-0.128, 0.176]$	$[-0.135, 0.190]$



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 $\lambda_Z = \lambda_\gamma$

WZ

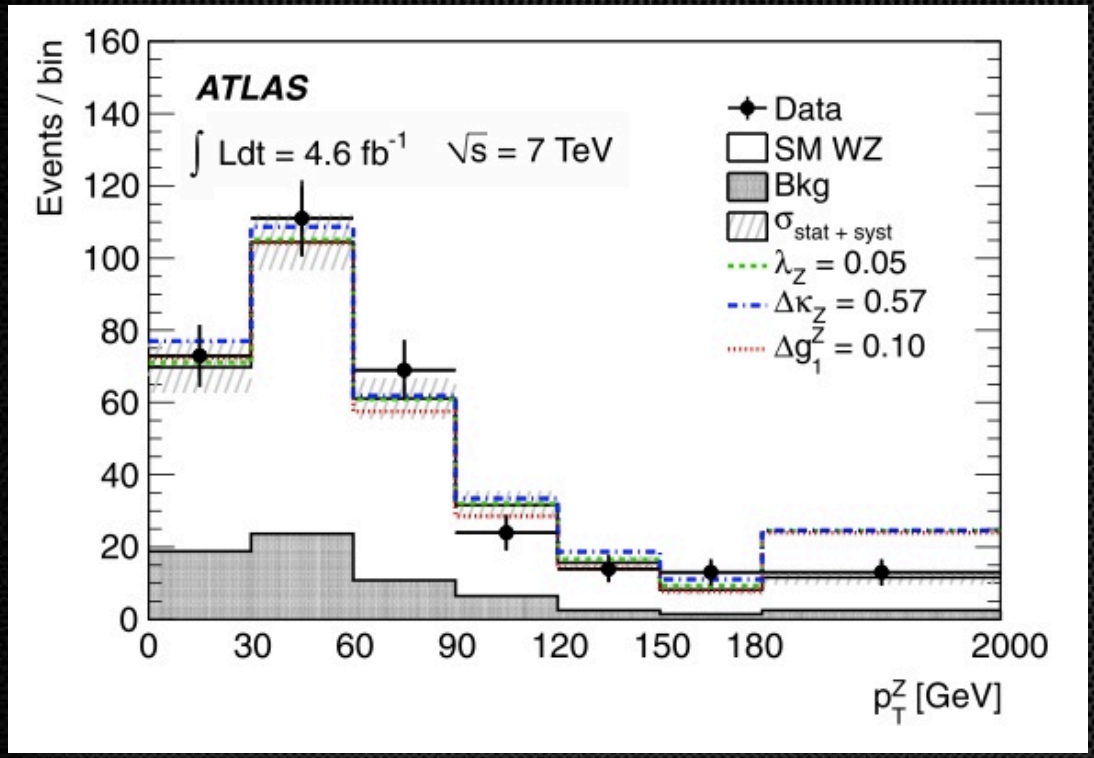
ATLAS: WZ→3lν analysis @ 8 TeV with 13 fb^{-1}

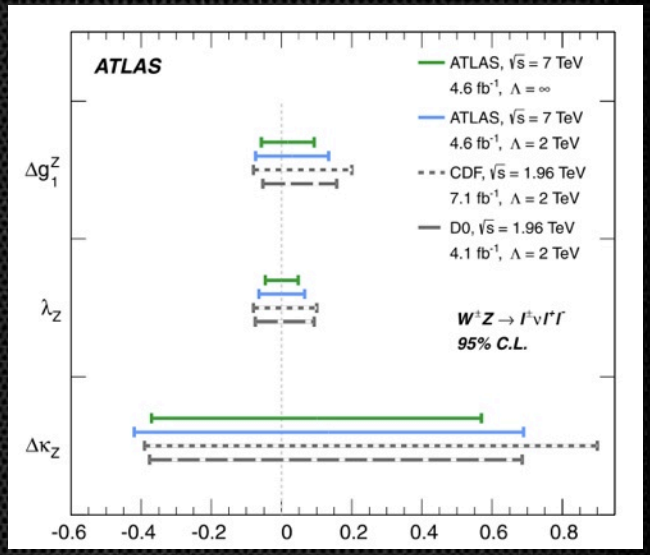
Channel	Cross Section [pb]
$\mu\mu\mu$	$19.1^{+1.4}_{-1.3}$(stat.) $^{+1.3}_{-1.3}$(syst.) $^{+0.6}_{-0.6}$(lumi.)
$e\mu\mu$	$21.4^{+1.9}_{-1.7}$(stat.) $^{+1.5}_{-1.5}$(syst.) $^{+0.7}_{-0.7}$(lumi.)
$ee\mu$	$21.9^{+1.8}_{-1.6}$(stat.) $^{+1.4}_{-1.4}$(syst.) $^{+0.7}_{-0.6}$(lumi.)
eee	$18.6^{+2.1}_{-1.9}$(stat.) $^{+1.9}_{-1.9}$(syst.) $^{+0.6}_{-0.6}$(lumi.)
Combined	$20.3^{+0.8}_{-0.7}$(stat.) $^{+1.2}_{-1.1}$(syst.) $^{+0.7}_{-0.6}$(lumi.)

Systematics: reco efficiencies, pT scale/resolution, isolation and impact parameter efficiencies, backgrounds (mainly Z+jets), luminosity(2.8%)

WZ

ATLAS: WZ→3lν analysis @ 7 TeV

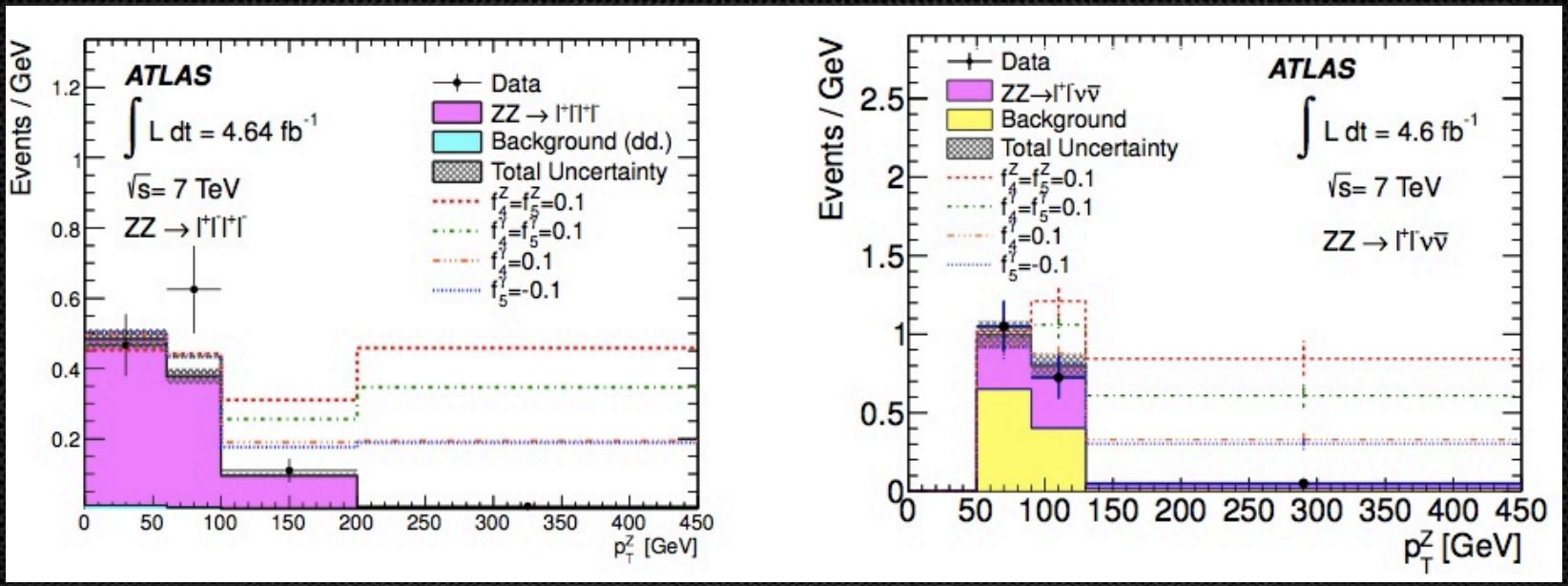




	Observed $\Lambda = 2$ TeV	Observed no form factor	Expected no form factor
Δg_1^Z	$[-0.074, 0.133]$	$[-0.057, 0.093]$	$[-0.046, 0.080]$
$\Delta\kappa_Z$	$[-0.42, 0.69]$	$[-0.37, 0.57]$	$[-0.33, 0.47]$
λ_Z	$[-0.064, 0.066]$	$[-0.046, 0.047]$	$[-0.041, 0.040]$

ZZ

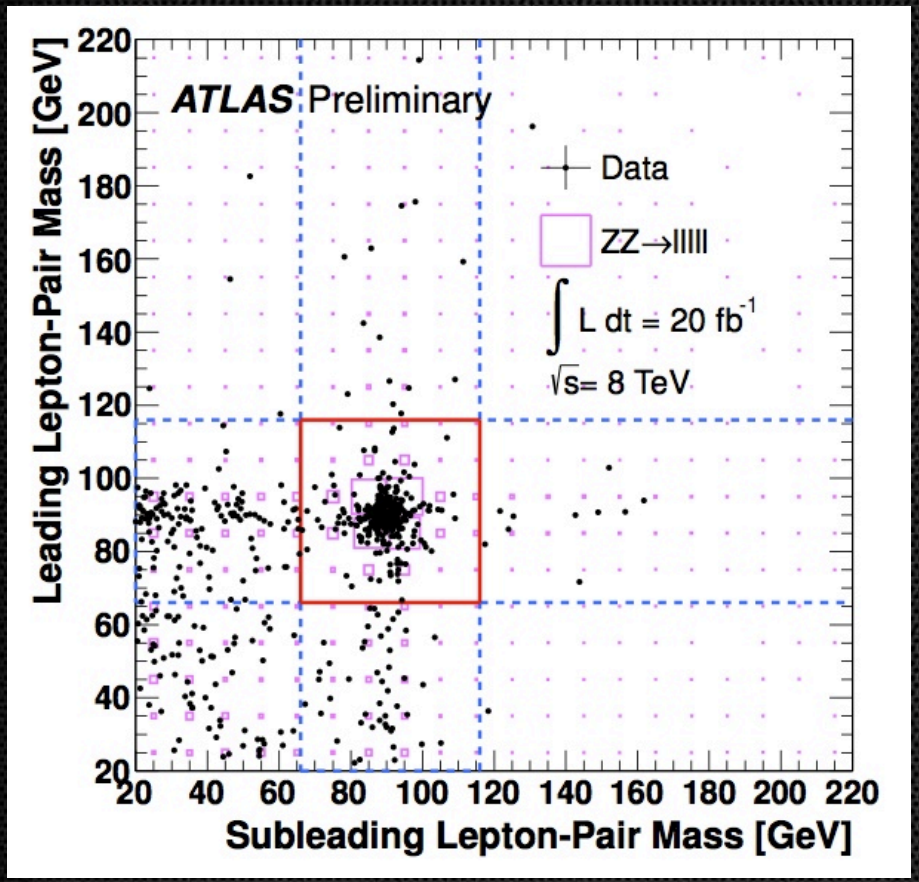
ATLAS: ZZ→4l analysis @ 7TeV



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

ZZ

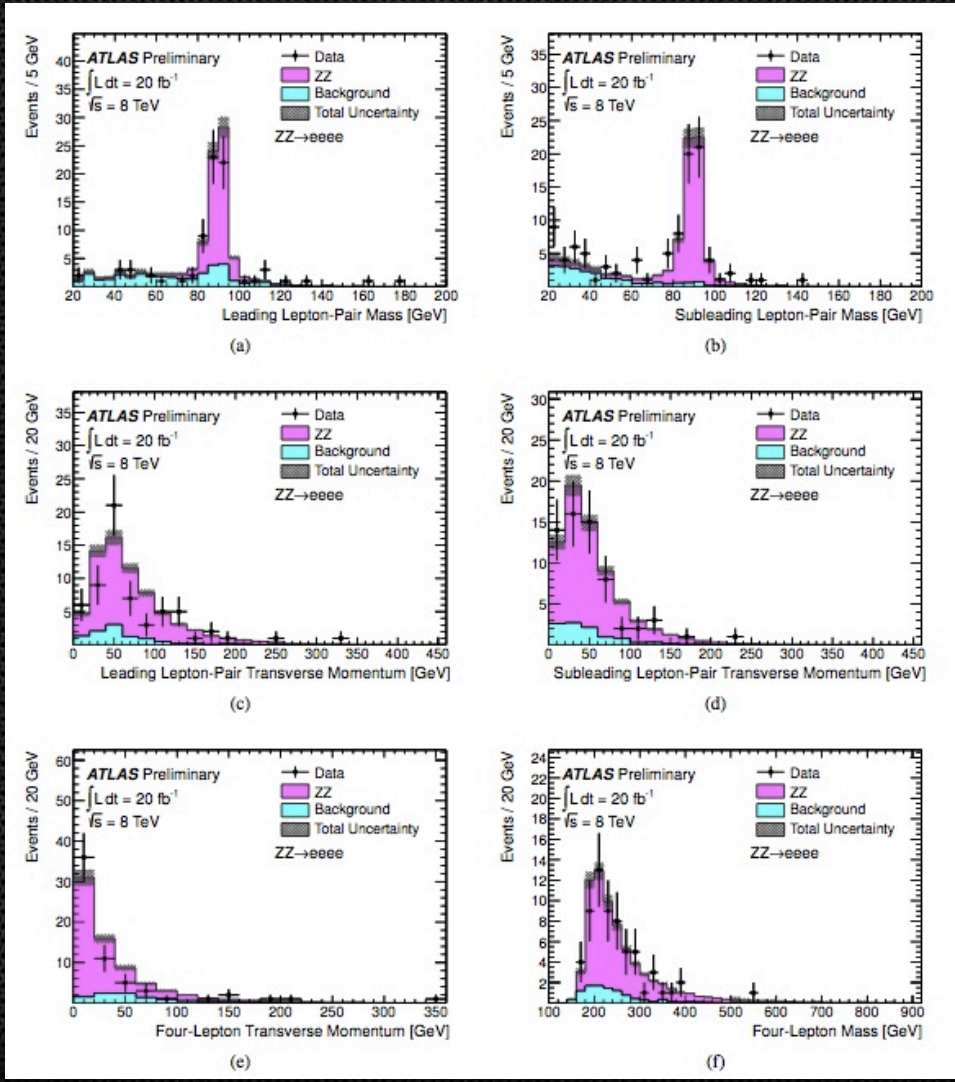
ATLAS: ZZ→4l analysis @ 8 TeV



Source	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Reconstruction Uncertainties				
Lepton identification and reconstruction	6.2%	1.2%	3.1%	2.8%
Lepton energy/momentum	0.4%	<0.1%	0.2%	0.1%
Lepton isolation and impact parameter	1.8%	2.6%	1.5%	1.6%
Trigger efficiency	<0.1%	0.2%	0.1%	0.1%
Total Reconstruction Uncertainty (C_{ZZ})	6.4%	2.8%	3.4%	3.3%
Theoretical Uncertainties				
PDF & Scale (C_{ZZ})	0.1%	0.1%	<0.1%	<0.1%
MC Generator Difference (C_{ZZ})	1.7%	0.9%	1.8%	1.5%
PDF & Scale (A_{ZZ})	1.0%			
MC Generator Difference (A_{ZZ})	0.8%			
Total for C_{ZZ}	6.6%	3.0%	3.9%	3.6%
Total for A_{ZZ}	1.3%			
Luminosity	2.8%			

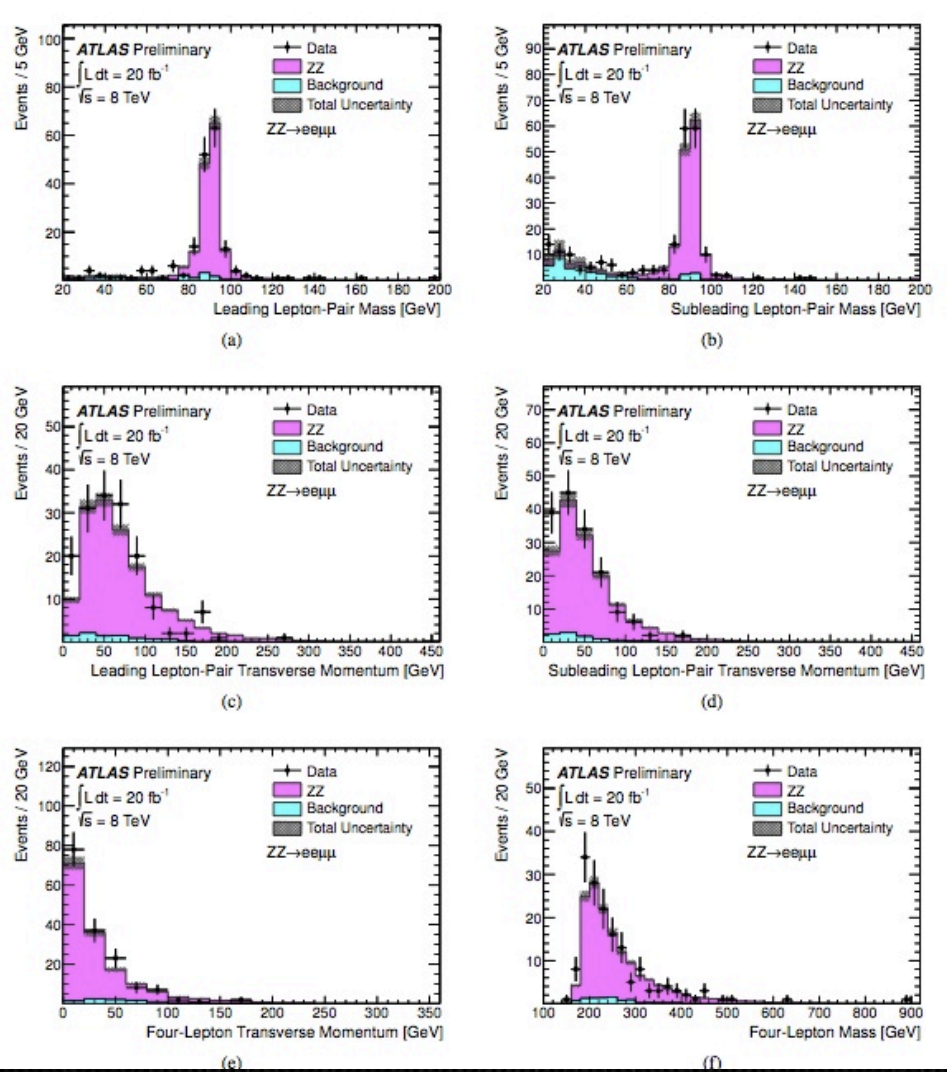
ZZ

ATLAS: ZZ→4l analysis @ 8 TeV



ZZ

ATLAS: ZZ→4l analysis @ 8 TeV



ZZ

ATLAS: ZZ→4l analysis @ 8 TeV