Measurements of Multi-boson production, Trilinear and Quadratic Gauge Couplings with the ATLAS detector

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on behalf of the ATLAS Collaboration

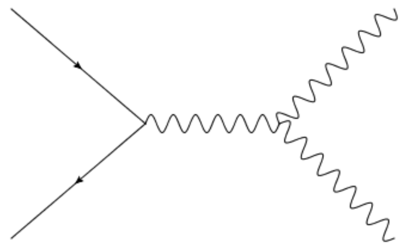
DIS2015 WG3:

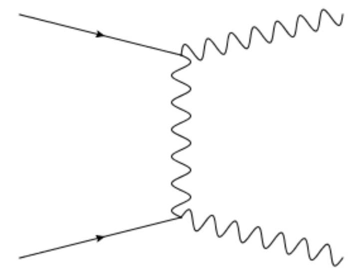
Electroweak, Higgs, and Beyond the Standard Model

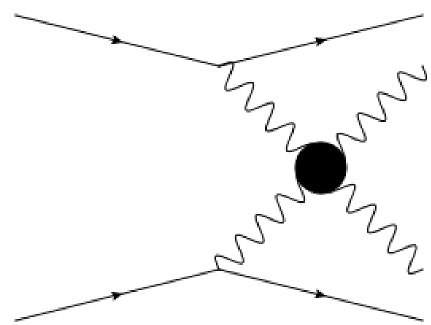
April 28, 2015

Outline

- Introduction to multi-boson physics
- Results from the following analyses:
  - WZ
  - WW
  - Semi-leptonic WW/WZ
  - Wγ/Zγ
  - ZZ
  - Zjj
  - Same sign WW
  - Wγγ
  - Simultaneous ttbar, WW, Z
- Overview of multi-boson cross section measurements
- Overview of limits on anomalous triple gauge couplings (aTGCs)







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Introduction: Multiboson physics (I)

- Multi-boson cross section measurements
  - Important test of the electroweak sector of the Standard Model
  - Sensitive to new physics particles that decay to EW bosons
  - Irreducible background for Higgs
- Common signatures
  - Combinations of W, Z, γ
  - Leptonic decays: High p_T, isolated e or μ
  - W boson:
    - Transverse momentum imbalance, E_T^{miss}, from neutrino
    - Transverse mass (m_T) selection
  - Z boson:
    - Mass window around Z pole mass

- Cross section measurement in **fiducial region**, defined by detector acceptance and selection requirements

$$\sigma^{fid} = \frac{N_{data} - N_{bkg}}{C \int \mathcal{L} dt}$$

- Extrapolate to **total** phase space for total production cross section

$$\sigma^{tot} = \frac{N_{data} - N_{bkg}}{A \cdot C \cdot Br \cdot \int \mathcal{L} dt}$$

N_{data} = number of data events

N_{bkg} = number of background events

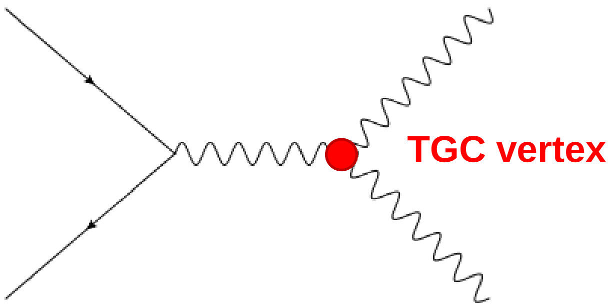
C = efficiency correction

A = fiducial acceptance

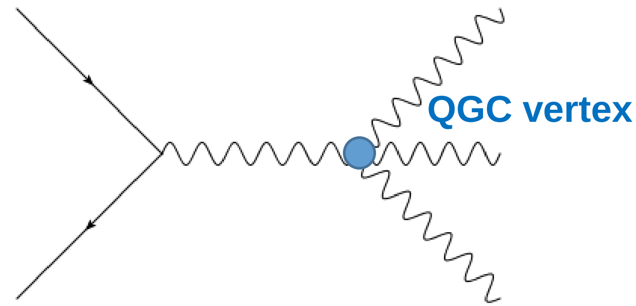
L = luminosity

Introduction: Multiboson physics (II)

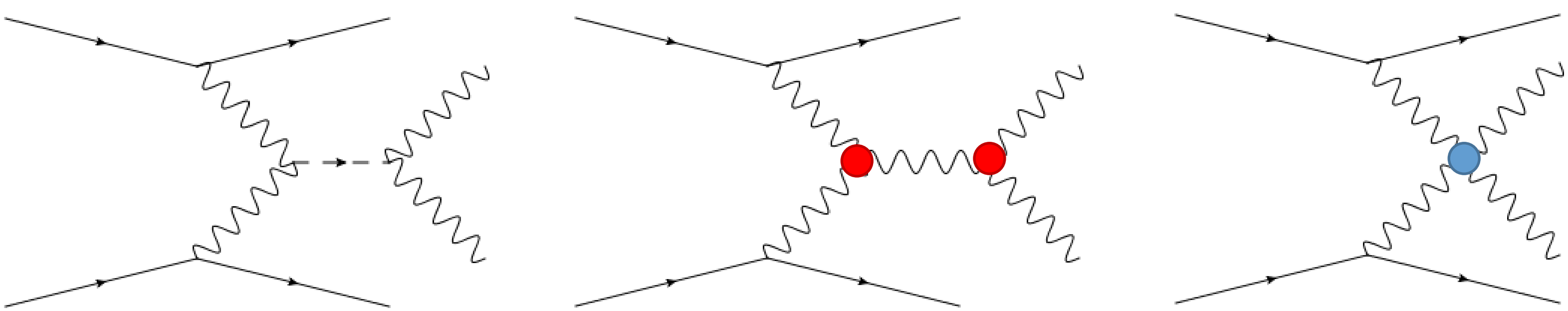
- Di-boson production is sensitive to anomalous triple gauge couplings (aTGCs)



- Triple boson production can be sensitive to anomalous quartic gauge couplings (aQGC)



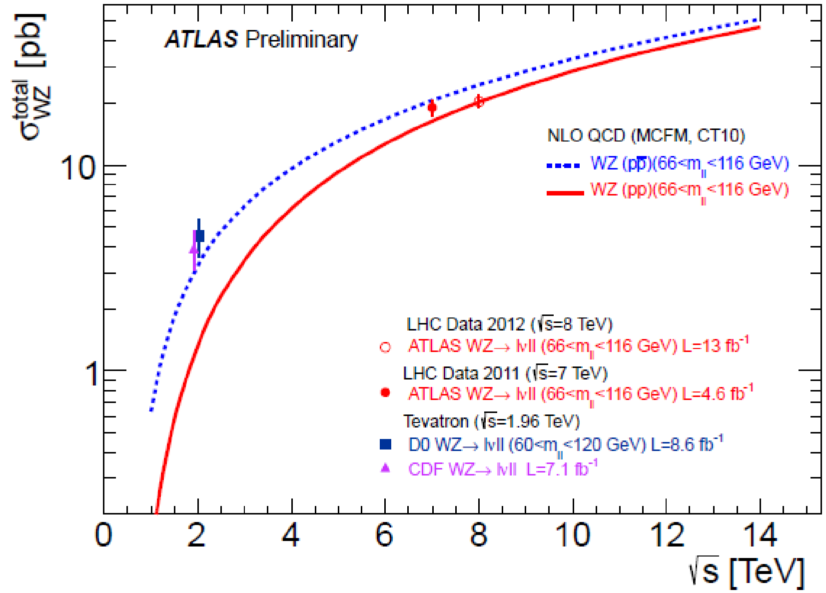
- Vector boson fusion/scattering can be sensitive to both

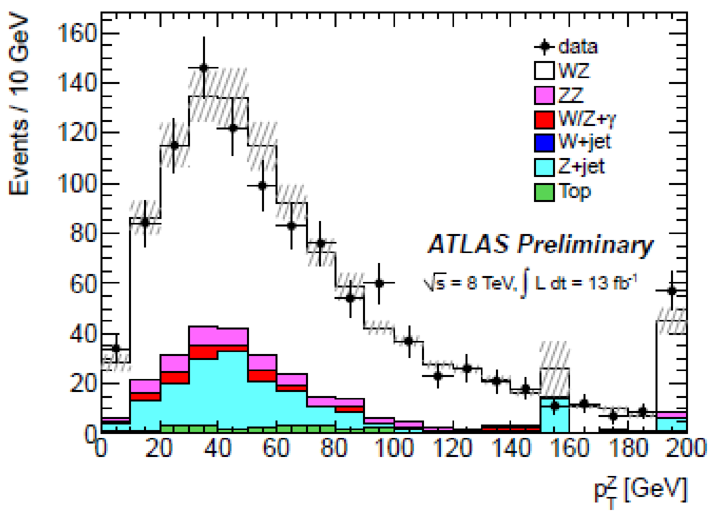


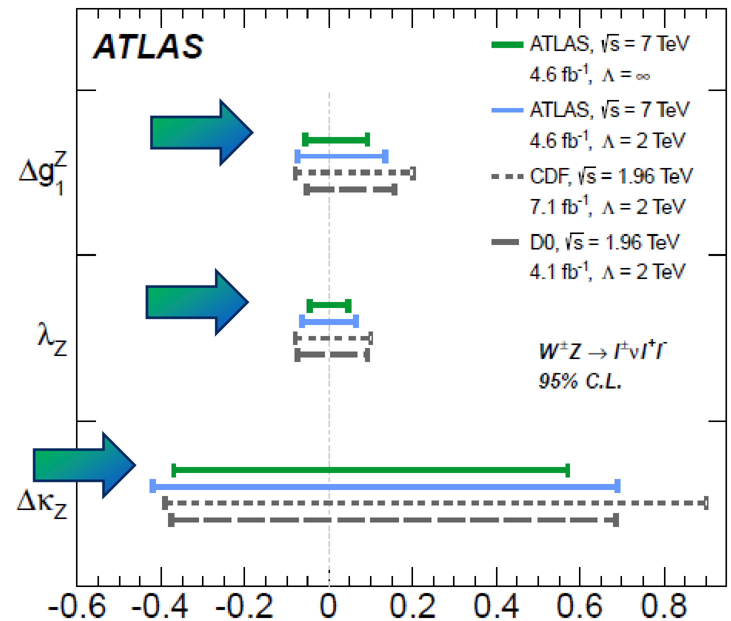
Anomalous couplings → deviations in cross section measurements and/or enhancements in high p_T or invariant mass regions

WZ Production

- Final state: (W→) lν (Z→) ll, l = e, mu
- Selection:
  - 3 leptons
  - $E_T^{miss} > 25$ GeV, $M_T^W > 20$ GeV
  - Z mass window: $| M_{ll} - M_Z | < 10$ GeV
- Backgrounds:
  - Z+jets (~17%*), ZZ (~5%*), Top (~2%*)
  - Data driven estimates for Z+jets and top backgrounds





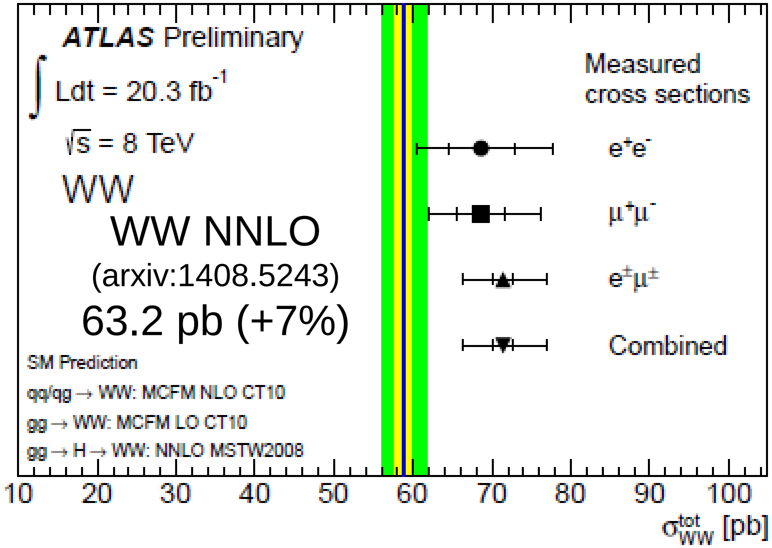


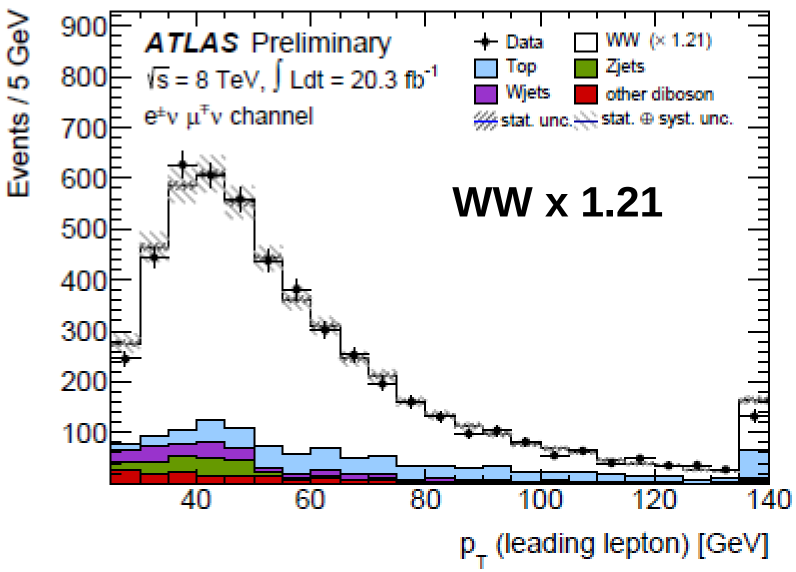
* As fraction of total events

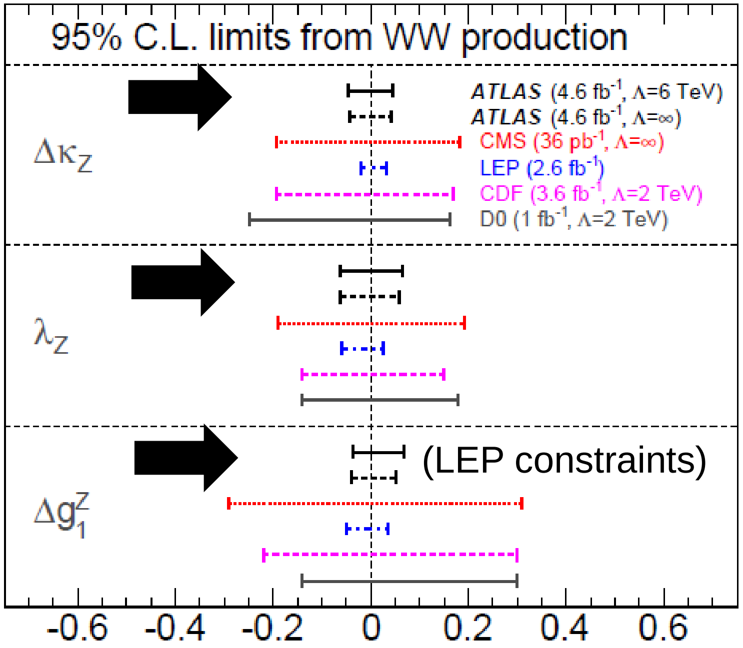
ATLAS-CONF-2014-033, Phys.Rev. D87 (2013) 112001

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

- Final state: lνlν, l = e, mu
- Selection:
  - 2 opposite sign leptons
  - Z veto in same flavor channels:
    - $|M_{ll} - M_Z| > 15$ GeV
  - Large E_T^{miss} to further suppress Drell-Yan (~5% of total)
  - Hard Jet Veto to suppress top (~14%)



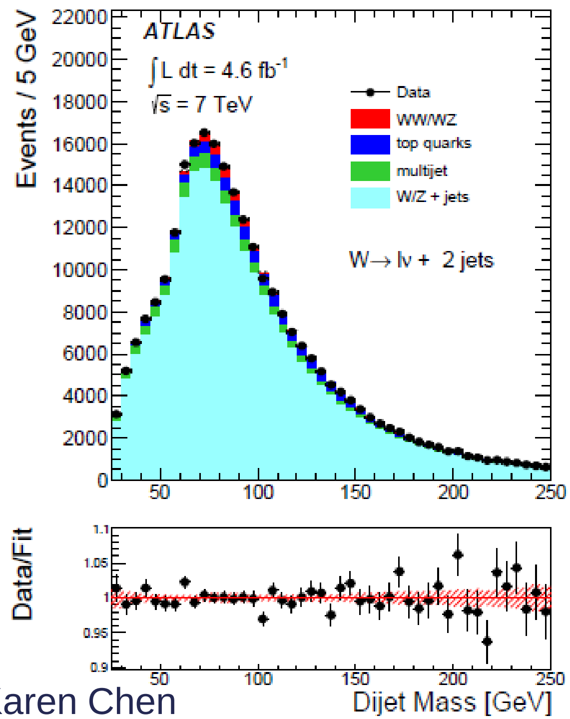




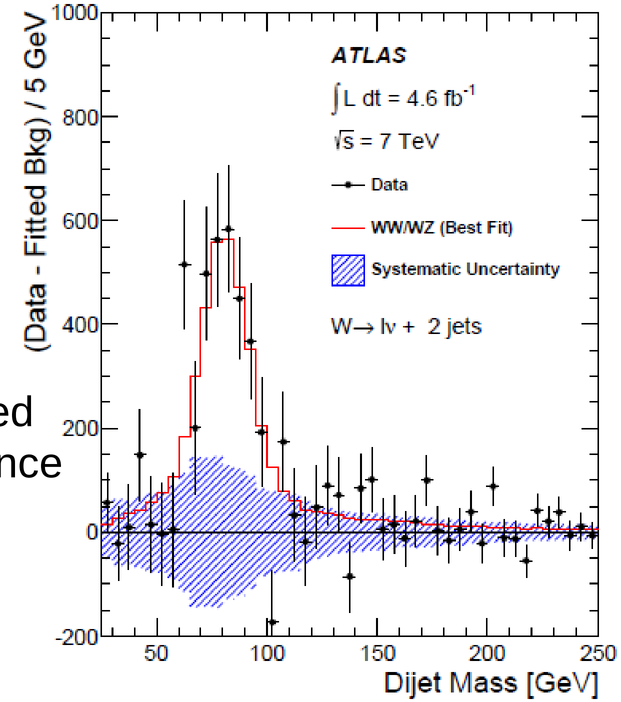
JHEP 1501 (2015) 049

WW/WZ Semileptonic Production (I)

- Final state: (W→) lν (W/Z→) jj, l = e, mu
- 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
  - $E_T^{miss} > 30$ GeV, $m_T^W > 40$ GeV, $|\Delta\varphi(\text{leading jet } E_T, E_T^{miss})| > 0.8$



- Backgrounds:
  - W+jets (~85%),Z+jets (~4%), Multijet (~4%), Top (~5%)



Observed Significance 3.4σ

$$\sigma_{\text{fid}} = 1.37 \pm 0.14\ (\text{stat.}) \pm 0.37\ (\text{syst.})\ \text{pb}$$

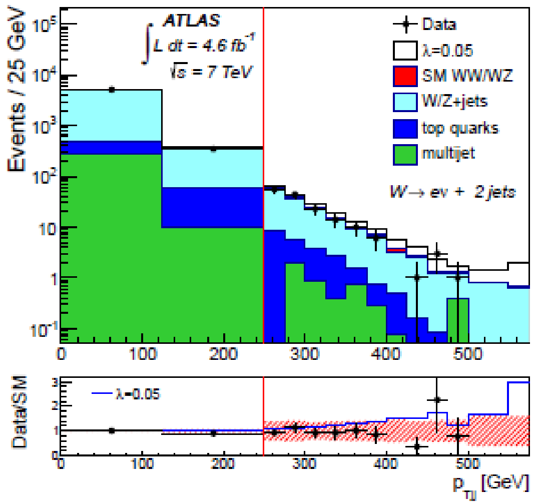
$$\sigma_{\text{tot}} = 68 \pm 7\ (\text{stat.}) \pm 19\ (\text{syst.})\ \text{pb}\,,$$

Standard Model prediction 61.1 ± 2.2 pb

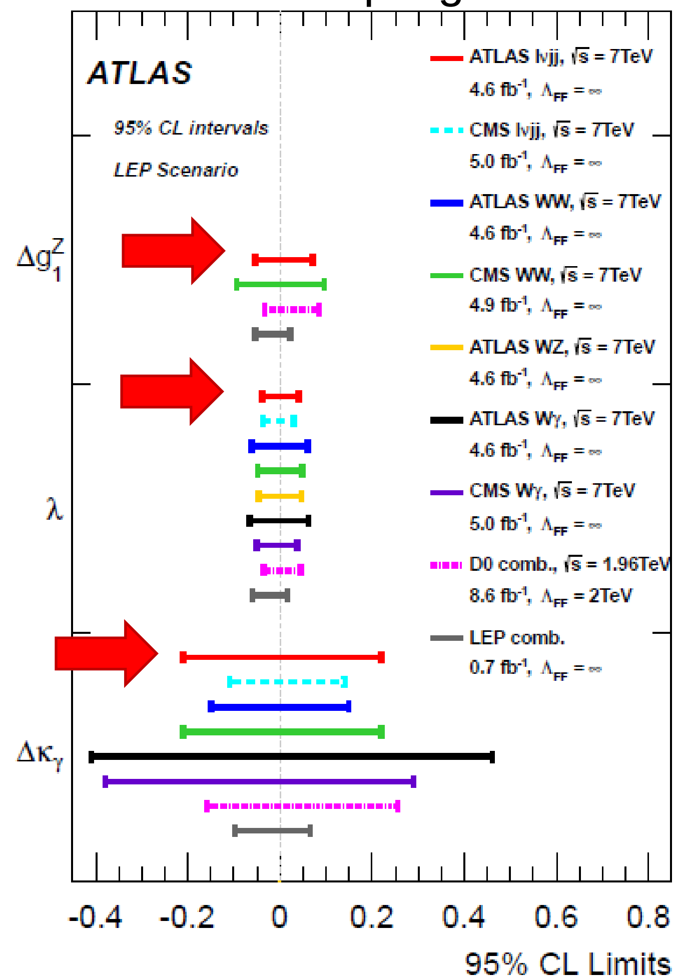
JHEP 1501 (2015) 049

WW/WZ Semileptonic Production (II)

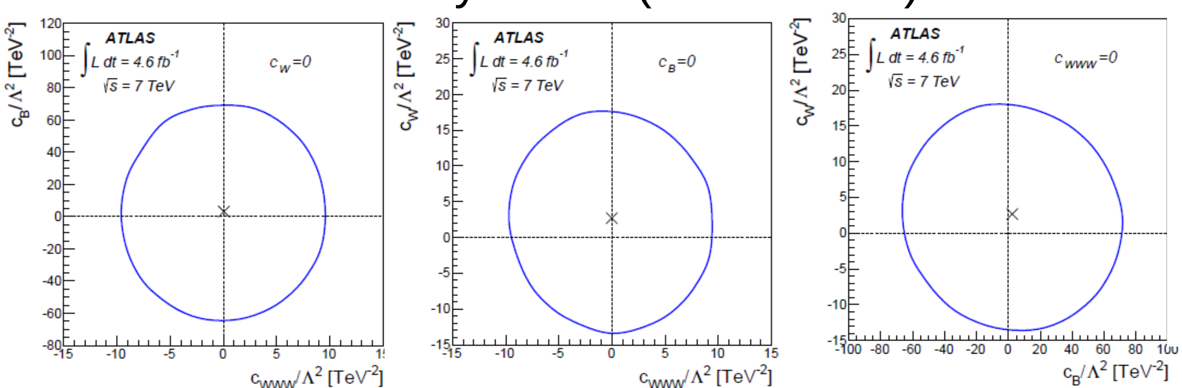
- $p_T(jj)$ used to extract limits on parameters in anomalous couplings framework and effective field theory



Anomalous couplings

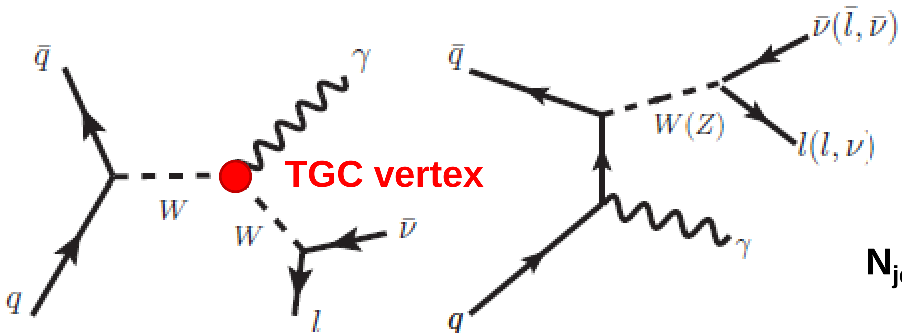


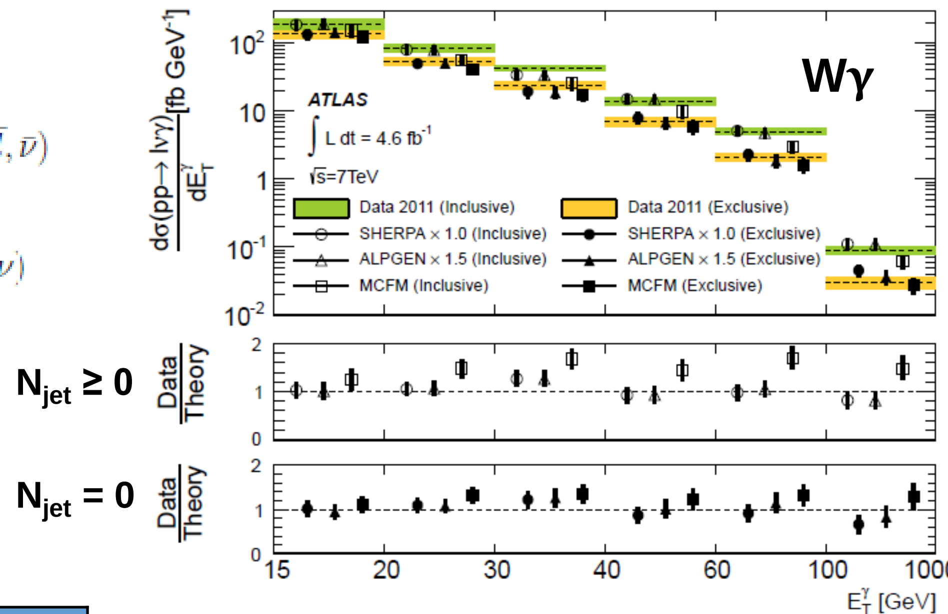
Effective field theory model (first at LHC!)



Phys. Rev. D 87, 112003

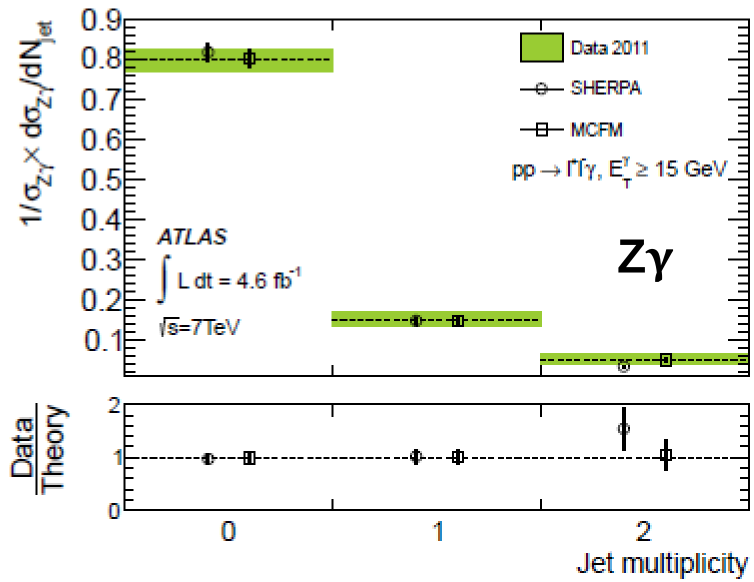
Wγ / Zγ Production (I)





Selection Highlights

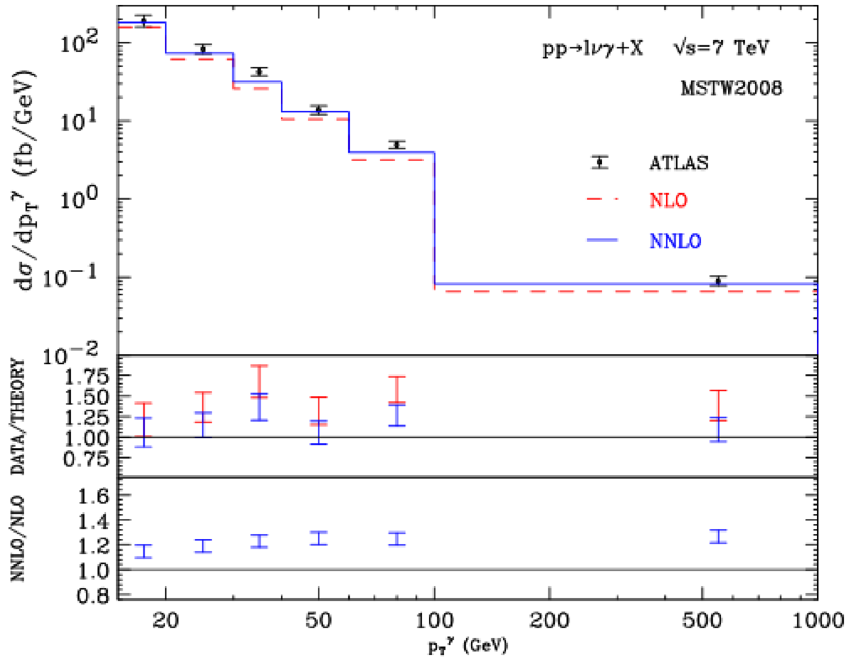
$(W\rightarrow)\ l\nu\ \gamma$	$(Z\rightarrow)\ ll\ \gamma$	$(Z\rightarrow)\ \nu\nu\ \gamma$
$p_T^{lep} > 25$ GeV, $E_T^{\gamma} > 15$ GeV		$E_T^{\gamma} > 100$ GeV
$E_T^{miss} > 35$ GeV	-	$E_T^{miss} > 90$ GeV
$m_T > 40$ GeV	$M(ll) > 40$ GeV	-
$p_T^{jet} > 30$ GeV		



- Differential cross section measurements in photon E_T (top) and jet multiplicity (bottom).
  - Exclusive: $N_{jet} = 0$, Inclusive: $N_{jet} \geq 0$

Wγ / Zγ Production (II)

Grazzini



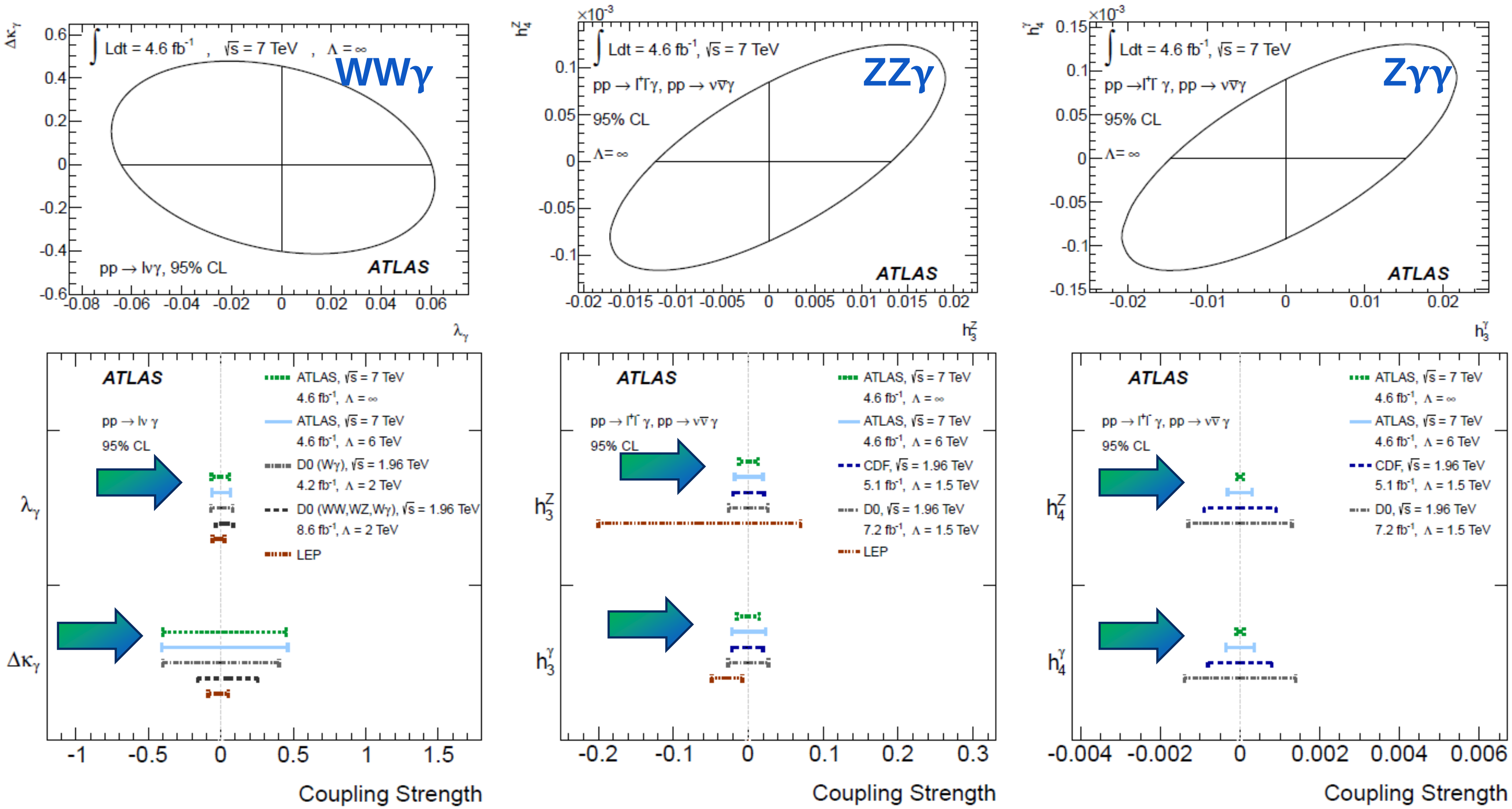
- NNLO calculation (arXiv:1407.1618)
  - Large radiative corrections for Wγ
  - 19% correction for Wγ
  - 6% increase for Zγ
- Agreement with data is improved
- Fiducial cross section with NLO and NNLO calculations below

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

Phys. Rev. D 87, 112003

Wγ / Zγ Production (III)

- Limits on anomalous couplings from fiducial measurement with $E_T^\gamma > 100$ GeV



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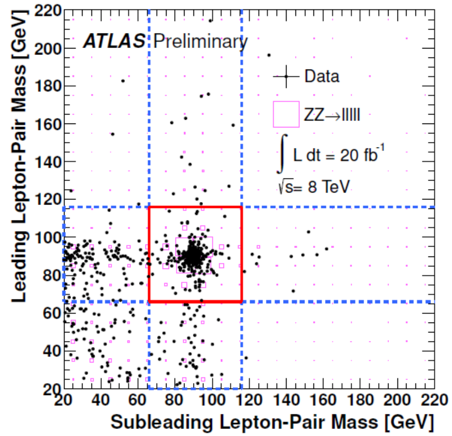
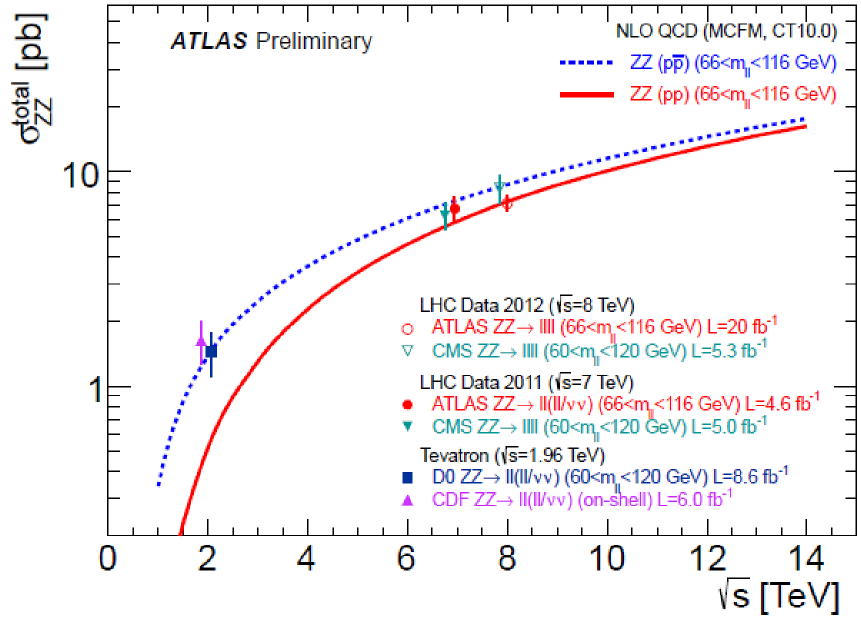
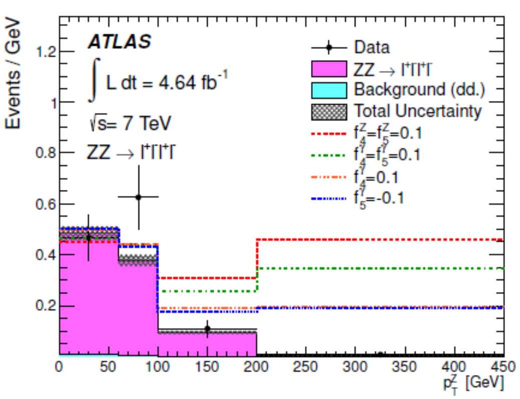
ZZ Production

- Final state: ZZ→l^+l^- l^+l^- and ZZ→l^+l^- $\nu\nu$
- Selection:
  - Opposite sign lepton pair(s) with M(ll) within Z mass window
  - For l^+l^- $\nu\nu$:
    jet veto
    axial-E_T^{miss} > 75 GeV

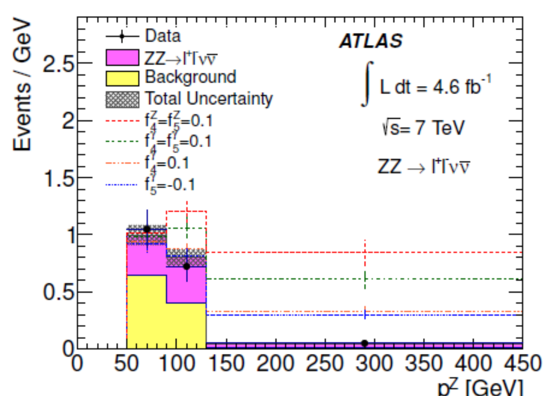


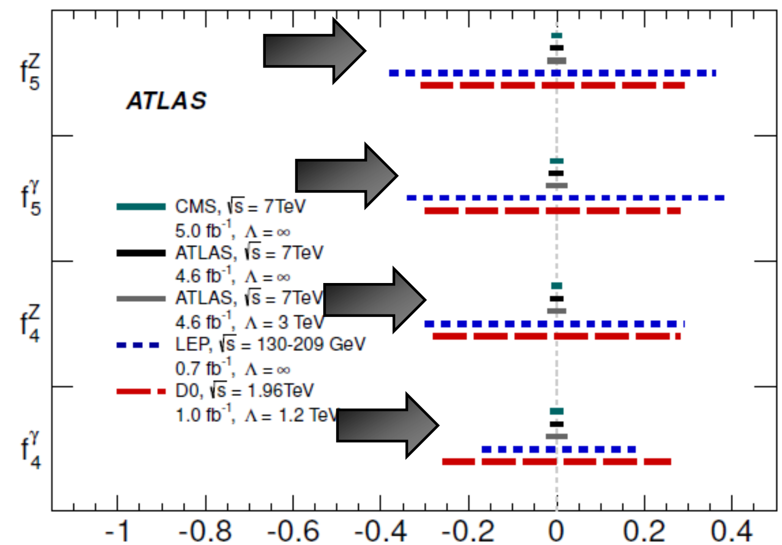


ZZ→llll



ZZ→llνν



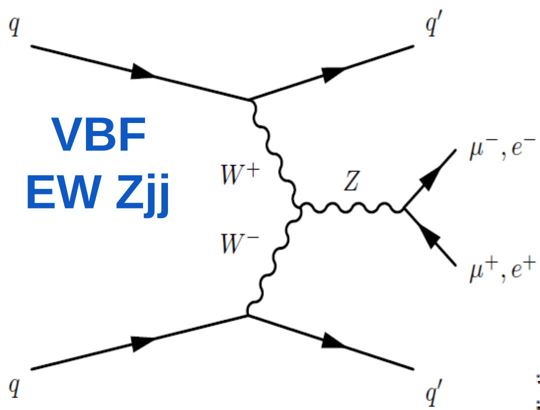


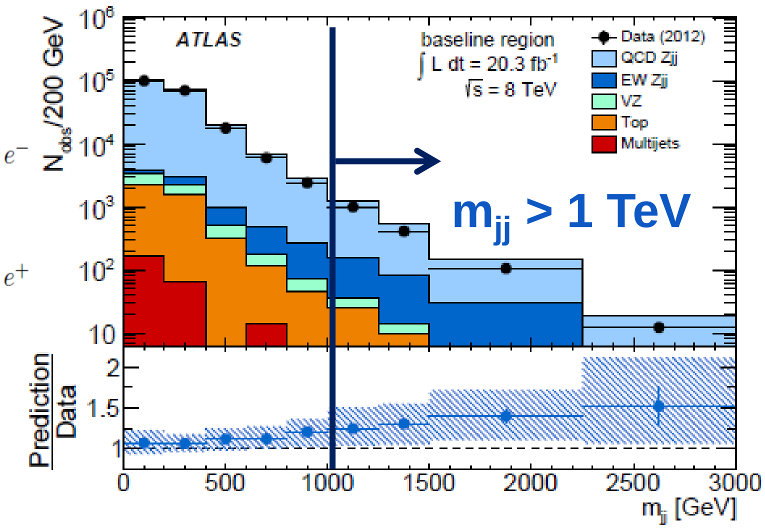
JHEP 1404 (2014) 031

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:
    - $p_T(ll) > 20$ GeV
    - $m_{jj} > 250$ GeV, $p_T^{balance} < 0.15$
    - No jets in rapidity gap between the two high p_T jets

VBF EW Zjj





- 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 > 5σ

$$\sigma_{\rm EW}\,(m_{jj} > 1\,{\rm TeV}) = 10.7 \pm 0.9\,({\rm stat})\ \pm 1.9\,({\rm syst})\ \pm 0.3\,({\rm lumi})\,{\rm fb},$$

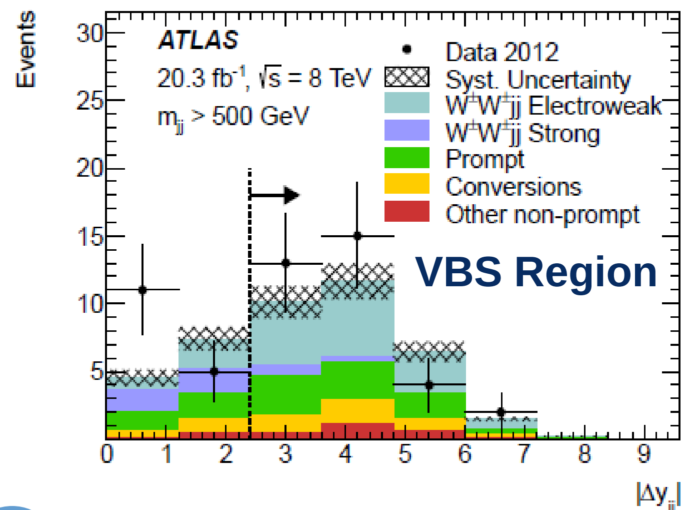
$$\text{theoretical prediction}\quad 9.38 \pm 0.05\,({\rm stat})\ ^{+0.15}_{-0.24}\,({\rm scale})\ \pm 0.24\,({\rm PDF})\ \pm 0.09\,({\rm model})\,{\rm fb}.$$

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (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	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Phys.Rev.Lett. 113 (2014) 141803

Vector boson scattering: $W^{\pm}W^{\pm}jj$ Production

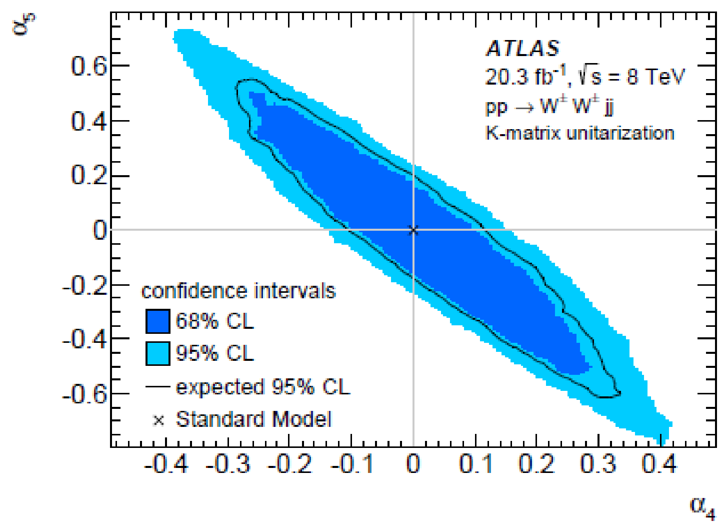
- Final state: $l^{\pm}\nu\ l^{\pm}\nu\ jj$
- Selection
  - Two high p_T leptons, ≥2 jets
  - m(ll) > 20 GeV
  - | m(ee) – m_Z | > 10 GeV
  - E_T^{miss} > 40 GeV
  - b-jet veto
  - Inclusive: m(jj) > 500 GeV
  - VBS: $|\Delta y_{jj}|$ > 2.4



First evidence of VBS WWjj at LHC!

Fiducial Cross section		
Strong and Electroweak $W^{\pm}W^{\pm}jj$	Observed	2.1 ± 0.5(stat) ± 0.3 (syst) fb Significance **4.5σ**
	SM Prediction	1.52 ± 0.11 fb
Electroweak $W^{\pm}W^{\pm}jj$ (VBS region)	Observed	1.3 ± 0.4(stat) ± 0.2(syst) fb Significance **3.6σ**
	SM Prediction	0.95 ± 0.06 fb

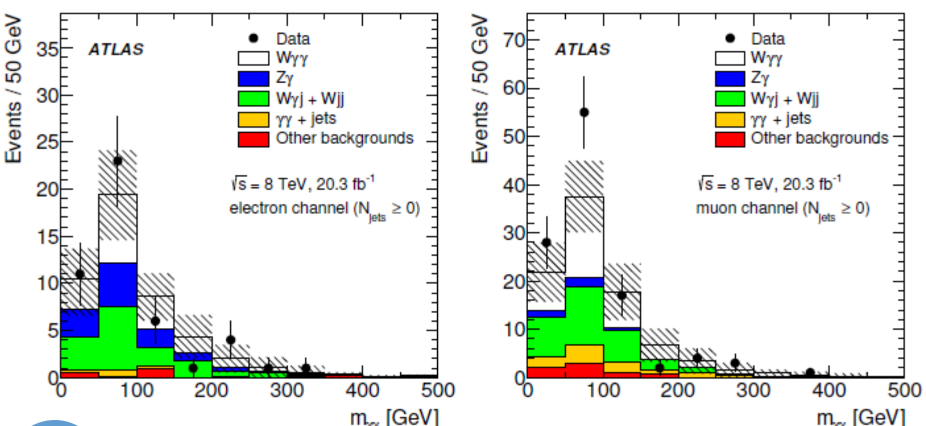
Measured fiducial cross section in VBS region used to set limits on aQGC's



arXiv:1503.03243

Wγγ Production

- Final state (W→)lν γγ
- Selection:
  - Lepton/photon p_T > 20 GeV
  - E_T^{miss} > 25 GeV
  - m_T > 40 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 Wγγ

Fiducial Cross section		
Inclusive (N_{jet} ≥ 0)	Measured	$6.1\ ^{+1.1}_{-1.0}$(stat) ± 1.2 (syst) ± 0.2(lumi.) fb Significance >**3σ**
	MCFM	2.90 ± 0.16 fb
Exclusive (N_{jet} = 0)	Measured	$2.9\ ^{+0.8}_{-0.7}$(stat) $^{+1.0}_{-0.9}$(syst) ± 0.1(lumi.) fb
	MCFM	1.88 ± 0.20 fb

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

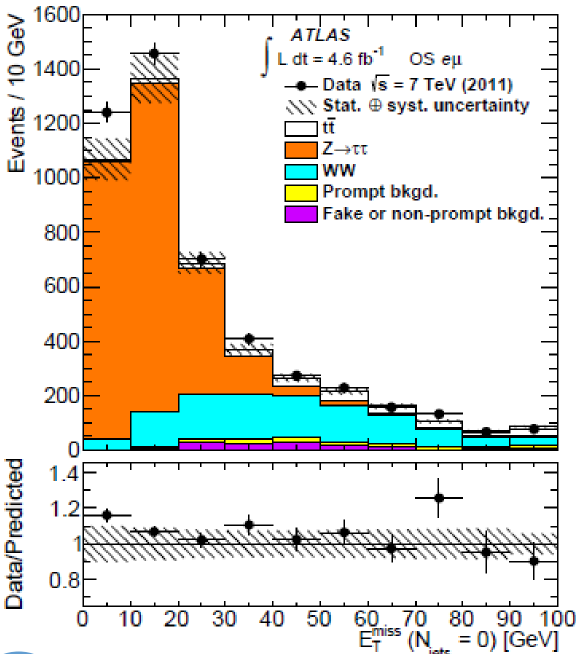
		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n=0$	f_{T0}/Λ^4	$[-0.9, 0.9]\times 10^2$	$[-1.2, 1.2]\times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8]\times 10^4$	$[-1.1, 1.1]\times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4]\times 10^4$	$[-1.9, 1.8]\times 10^4$
$n=1$	f_{T0}/Λ^4	$[-7.6, 7.3]\times 10^2$	$[-9.6, 9.5]\times 10^2$
	f_{M2}/Λ^4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

Phys.Rev. D91 (2015) 052005

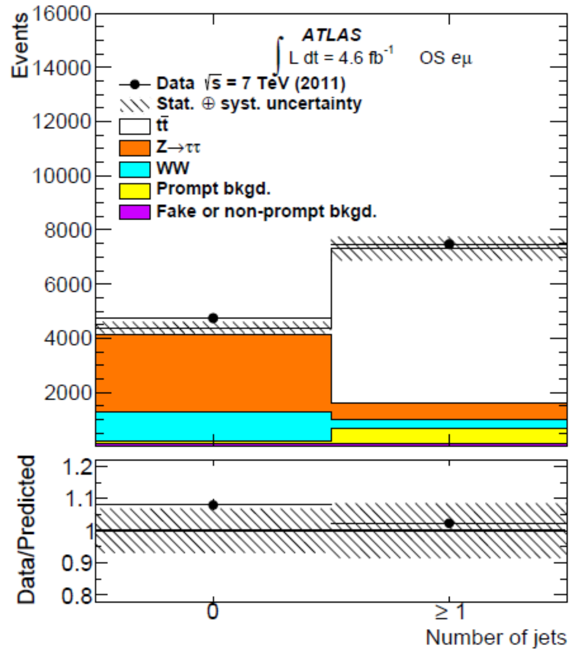
Simultaneous measurement: ttbar, W^+W^-, $Z \rightarrow \tau\tau$

- Final state: oppositely charged electron and muon
- Separate processes by E_T^{miss} and jet multiplicity
  - $N_{jets} \geq 1$ dominated by ttbar
  - $N_{jets} = 0$ and low/high E_T^{miss} dominated by Drell-Yan/WW
- Data driven estimate for fake or non-prompt backgrounds using matrix method

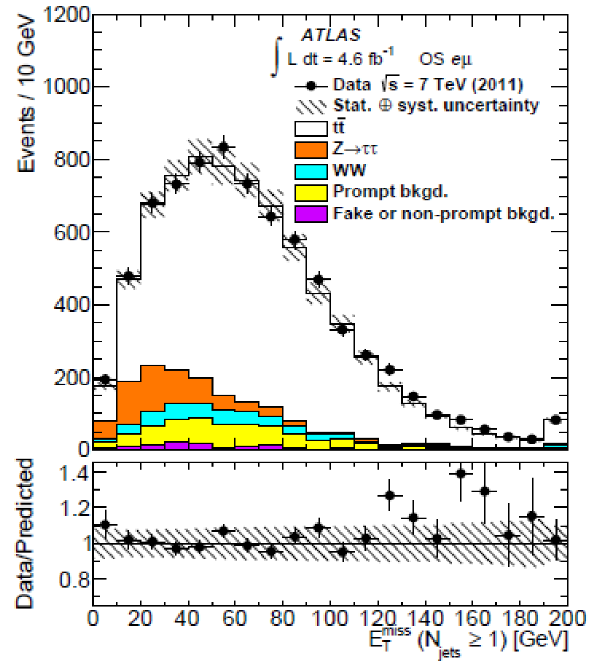
E_T^{miss} ($N_{jets} = 0$)



N_{jets}

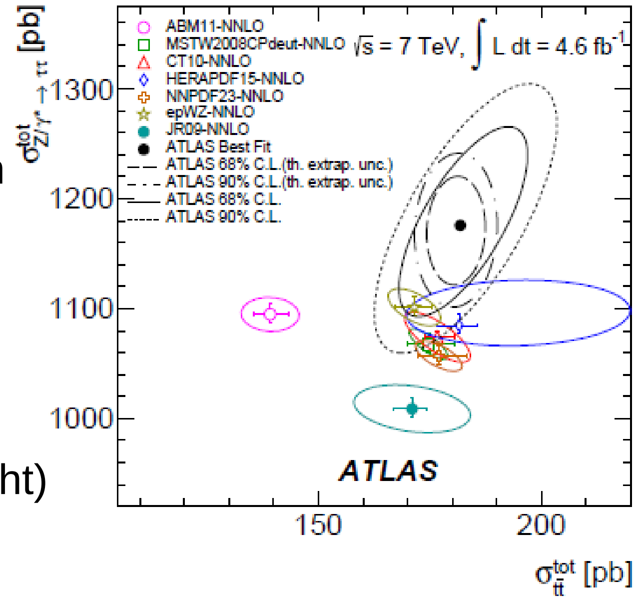


E_T^{miss} ($N_{jets} \geq 1$)

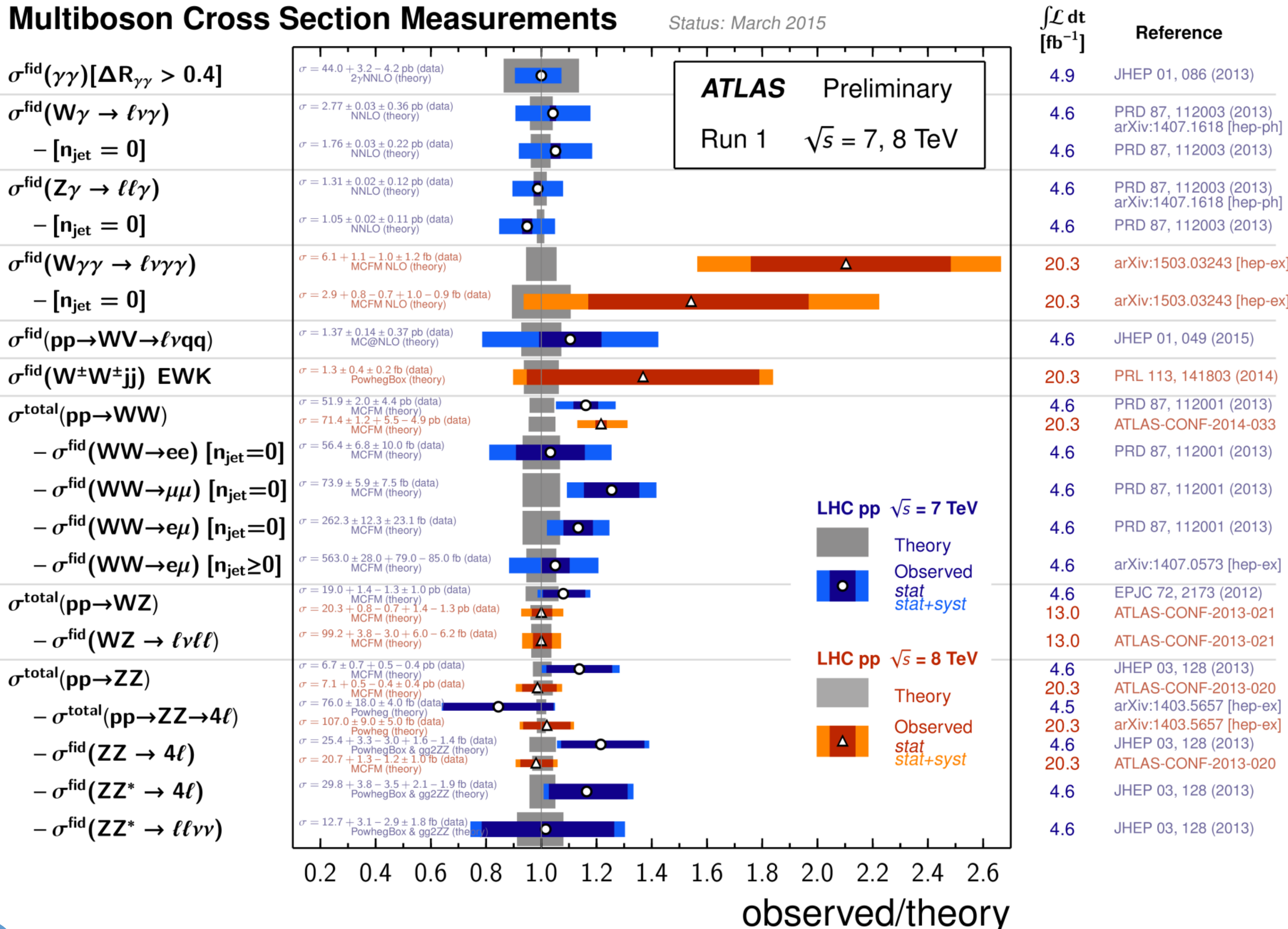


Simultaneous measurement: ttbar, W^+W^-, $Z \rightarrow \tau\tau$

- Simultaneous fit using templates of E_T^{miss} and jet multiplicity distributions
  - Normalizations for each process are free parameters in the fit
- Results with correlated PDFs:
  - NLO calculations underestimates the data for ttbar and Z
  - NNLO calculations generally describe the data well (right)
  - Comparison to dedicated measurements and theory (below)



Process	Source	σ_X^{tot} [pb]	Stat.	Syst.	Lumi.	Beam	Total	$\int \mathcal{L}\,dt$ [fb^{-1}]
$t\bar{t}$	Simultaneous	181	3	10	3	3	11	4.6
	Dedicated	183	3	4	4	3	7	4.6
	NNLO QCD	177					11	
WW	Simultaneous	53.3	2.7	7.7	1.0	0.5	8.5	4.6
	Dedicated	51.9	2.0	3.9	2.0		4.9	4.6
	NLO QCD	49.2	**(With gg→H→WW)**				2.3	
$Z/\gamma^* \rightarrow \tau\tau$	Simultaneous	1174	24	80	21	9	87	4.6
	Dedicated ($e\mu$)	1170	150	90	40		170	0.036
	NNLO QCD	1070					54	


Multiboson Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
∫ℒ dt [fb⁻¹]
Reference
σfid(γγ)[ΔRγγ > 0.4]
σfid(Wγ → ℓνγ)
− [njet = 0]
σfid(Zγ → ℓℓγ)
− [njet = 0]
σfid(Wγγ → ℓνγγ)
− [njet = 0]
σfid(pp→WV→ℓνqq)
σfid(W±W±jj) EWK
σtotal(pp→WW)
− σfid(WW→ee) [njet=0]
− σfid(WW→μμ) [njet=0]
− σfid(WW→eμ) [njet=0]
− σfid(WW→eμ) [njet≥0]
σtotal(pp→WZ)
− σfid(WZ → ℓνℓℓ)
σtotal(pp→ZZ)
− σtotal(pp→ZZ→4ℓ)
− σfid(ZZ → 4ℓ)
− σfid(ZZ* → 4ℓ)
− σfid(ZZ* → ℓℓνν)
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
4.9 JHEP 01, 086 (2013)
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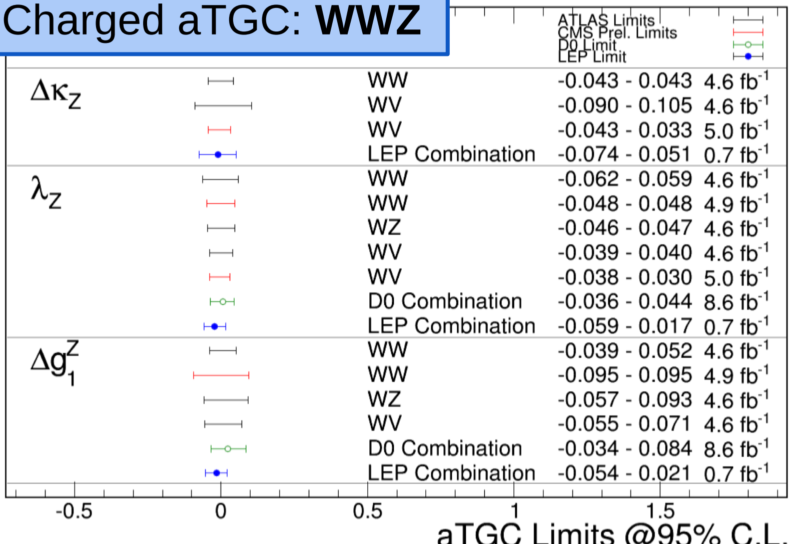
4.6 JHEP 03, 128 (2013)
4.6 JHEP 03, 128 (2013)
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
observed/theory

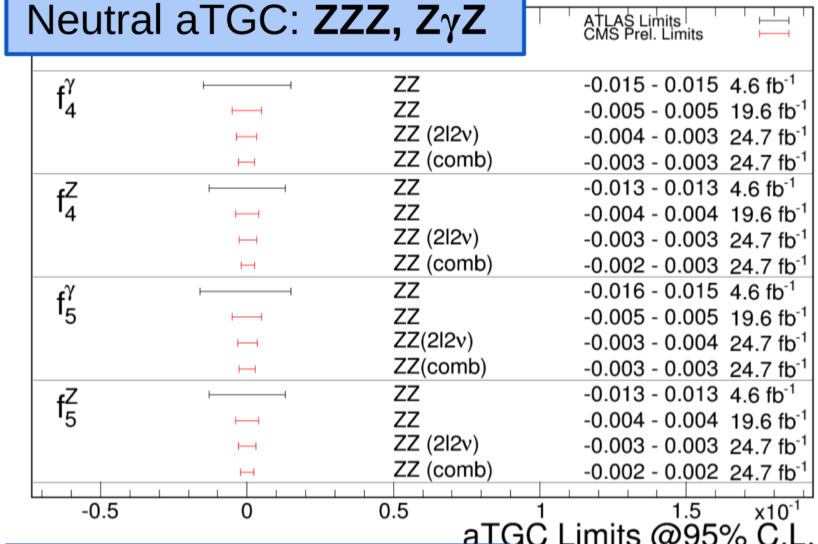
Summary of aTGC Limits at LHC

References

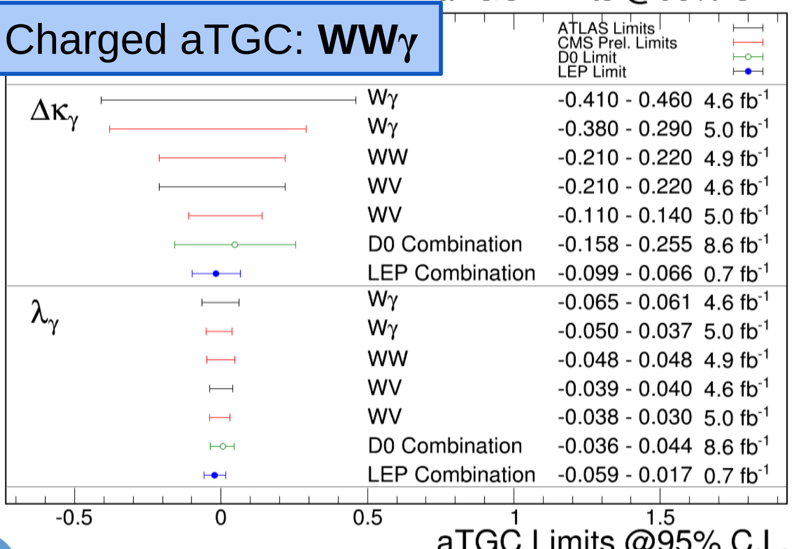
Charged aTGC: **WWZ**



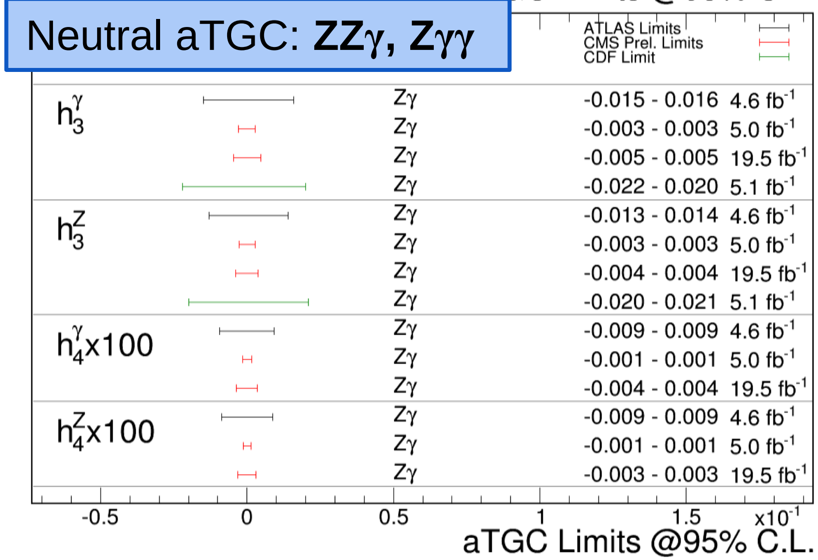
Neutral aTGC: **ZZZ, Zγ Z**



Charged aTGC: **WWγ**

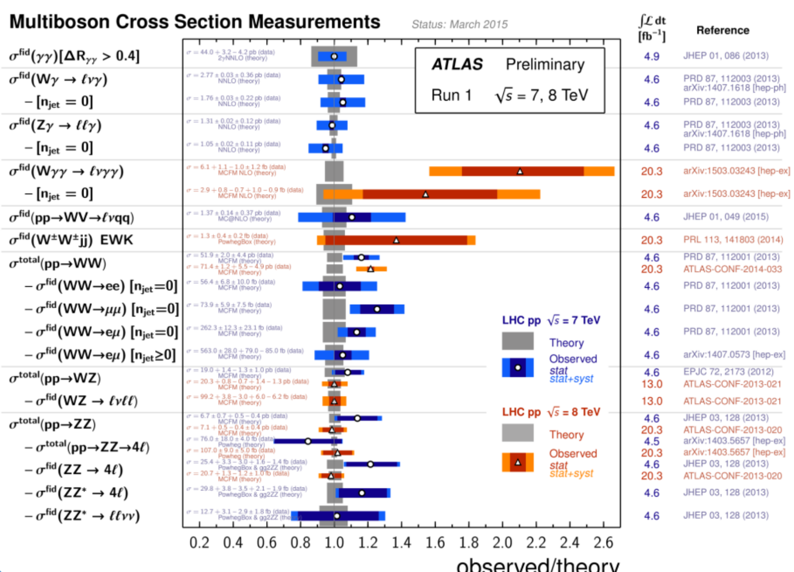


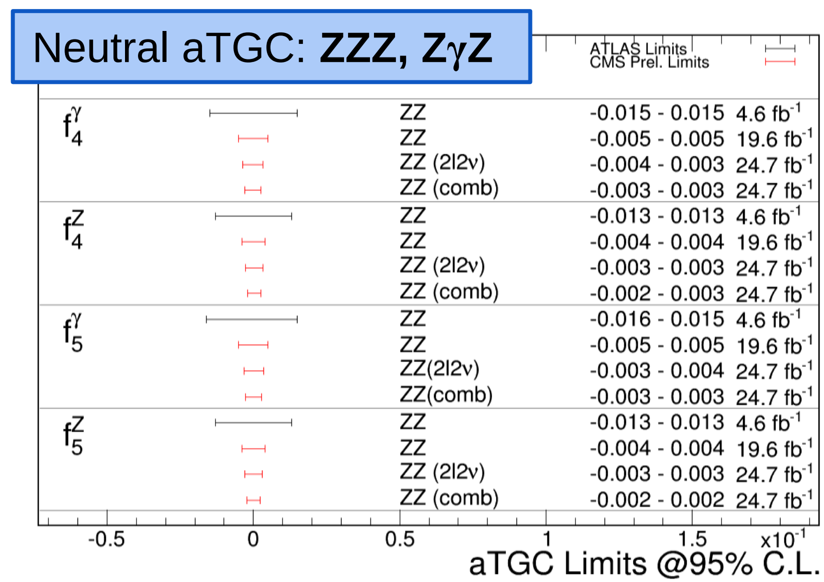
Neutral aTGC: **ZZγ, Zγγ**



Conclusions

- Summarized multi-boson results with ATLAS
  - Fiducial and total cross sections, differential cross sections
    - Generally good agreement with theory predictions
  - Limits on anomalous triple/quartic gauge couplings
    - Each analysis will be more sensitive to some couplings than others
    - Measurements with different final states will give complementary results
  - First evidence of VBS W±W±jj and Wγγ tri-boson production
- More multi-boson analyses at 8 TeV are on their way!





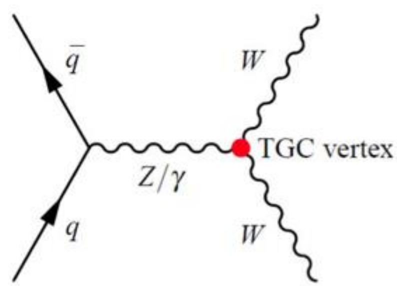
Backup

Anomalous triple gauge couplings (aTGCs)

- General Lagrangian for WWZ or WWγ vertex that conserves C and P separately:

$$\mathcal{L}/g_{WWV} = i g_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\,\mu} V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + i \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu{}_\nu V^{\nu\rho}$$

- For SM: $g_1^V = 1$, $k^V = 1$, $\lambda^v = 0$



coupling	parameters	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_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}^γ, f_{50}^γ	ZZ

- For non-SM values, this vertex will violate unitarity. We can introduce form factors to restore unitarity:
  - $s = m_{WW}^2$ and Λ is the scale for new physics (~TeV range)

$$\Delta g_1^V \to \frac{\Delta g_1^V}{(1+\hat{s}/\Lambda^2)^2}, \qquad \Delta\kappa^V \to \frac{\Delta\kappa^V}{(1+\hat{s}/\Lambda^2)^2}, \qquad \lambda^V \to \frac{\lambda^V}{(1+\hat{s}/\Lambda^2)^2}$$

Effective Field Theory (EFT)

- Expand Lagrangian to include higher order dim-6 operators, O

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- The C and P conserving operators relevant to triple gauge boson interactions

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi) B^{\mu\nu}(D_\nu\Phi)$$

- Can relate the anomalous couplings to these couplings strengths

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}\Delta g_1^Z$$
$$\frac{c_B}{\Lambda^2} = \frac{2}{m_Z^2}(\Delta\kappa^\gamma - \Delta\kappa^Z)$$
$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda$$