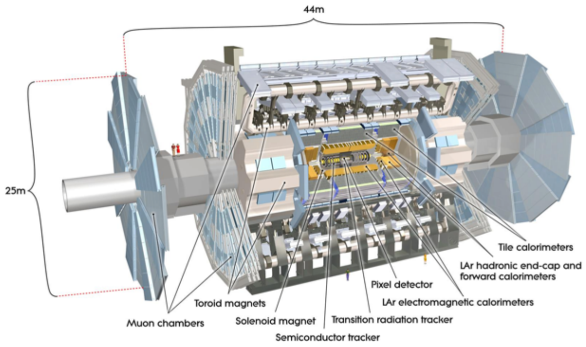
Multi-boson production at ATLAS



Al Goshaw
(Duke University)
for the ATLAS Collaboration

PHENO2016, Pittsburgh
May 10, 2016

A broad menu of EWK boson studies at the LHC

Collisions	Measurement				Production	EWK Study
p + p	→	V	+	0 jets	EWK s-channel	
at	→	V	+	2 forward jets	VBF	TGC
7,8,13	→	V V'	+	0 jets	EWK s-channel	TGC
TeV	→	V V'	+	2 forward jets	VBS	QGC
	→	V V' V''	+	0 jets	EWK s-channel	QGC

Thanks to the LHC

From the excellent performance of ATLAS and CMS

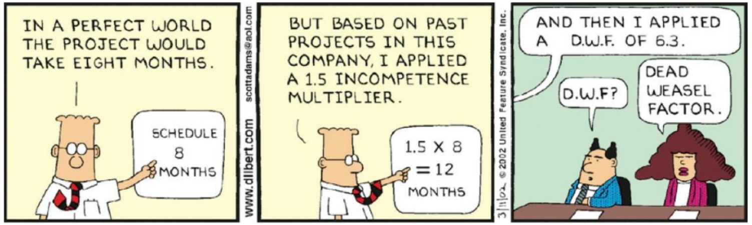
Studies using increasingly Precise SM theory calculations

Test the SM and look for BSM physics

Thanks to CERN and the LHC …

pp collisions Typical data set analyzed by ATLAS

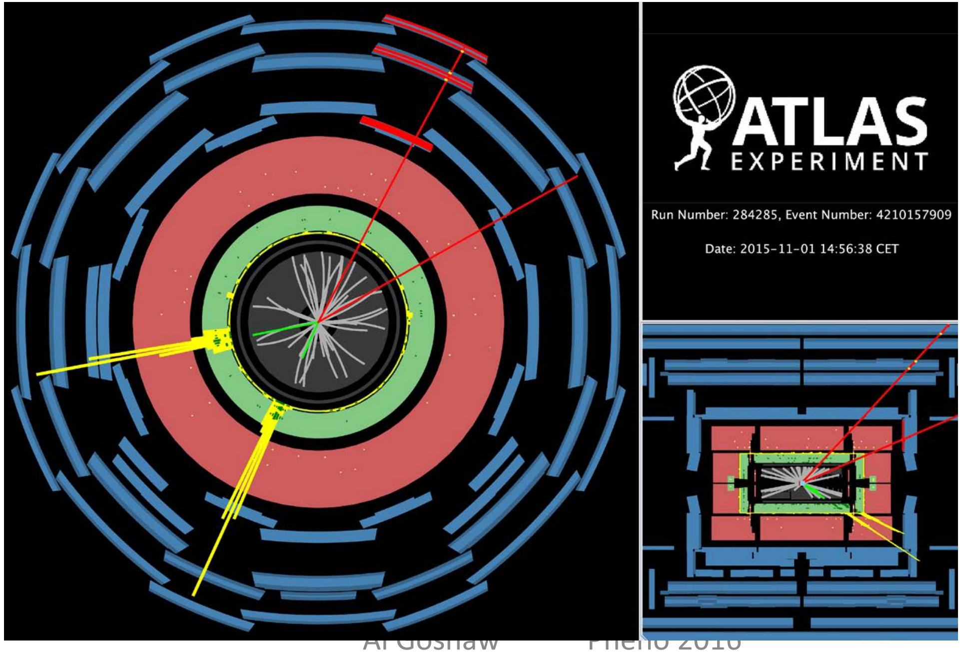
7 TeV	~ 5 fb^{-1}
8 TeV	~ 20 fb^{-1}
13 TeV	2015 data sample of 3.2 fb^{-1}
13 TeV	2016 first collisions occurring now …
	Goal ~ 25 fb^{-1} by end of year *



* modulo DWF

Beautiful detector performance …

$p + p \rightarrow Z(\mu^+ \mu^-) + Z(e^+ e^-) + \ldots$ at 13 TeV



Recent ATLAS measurements for VV'and VVV

Di - boson

- $Z\ \gamma$ 8 TeV
- $W^{\pm}\ W^{\mp}$ 8 TeV
- $W^{\pm}\ W^{\pm}$ 8 TeV
- $W^{\pm}\ Z$ 8 TeV
- $Z\ Z$ 13 TeV
- $W^{\pm}\ Z$ 13 TeV

approved today!

Tri - boson

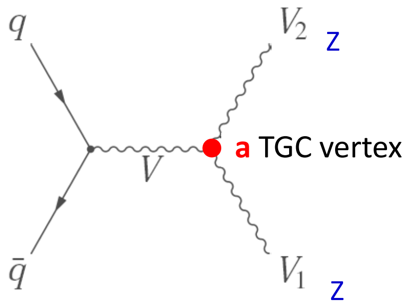
- $Z\ \gamma\ \gamma$ 8 TeV
- $W^{\pm}\ \gamma\ \gamma$ 8 TeV

Selected new results

Make comparisons to the best available SM calculations

Search for new physics via aTGC and aQGC

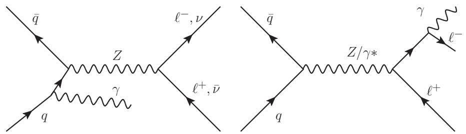
Di-boson production and TGC studies



Coupling	Parameters	Channel
WWγ	$\lambda\gamma, \Delta k\gamma$	WW, Wγ
WWZ	$\lambda Z, \Delta kZ, \Delta g_1^Z$	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZγZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ

$p + p \rightarrow Z + \gamma + \ldots$ at 8 TeV

arxiv:1604.05232



- Use Z decays to $e^+ e^-$, $\mu^+ \mu^-$ and $\nu \nu$ from 20.3 fb^{-1} of data.

- Cross sections measured for $Z(l^+ l^-) + \gamma$ ($E_T(\gamma) > 15$ GeV; $Z(l^+ l^-) > 40$ GeV) and for $Z(\nu \nu) + \gamma$ ($E_T(\gamma) > 130$ GeV).

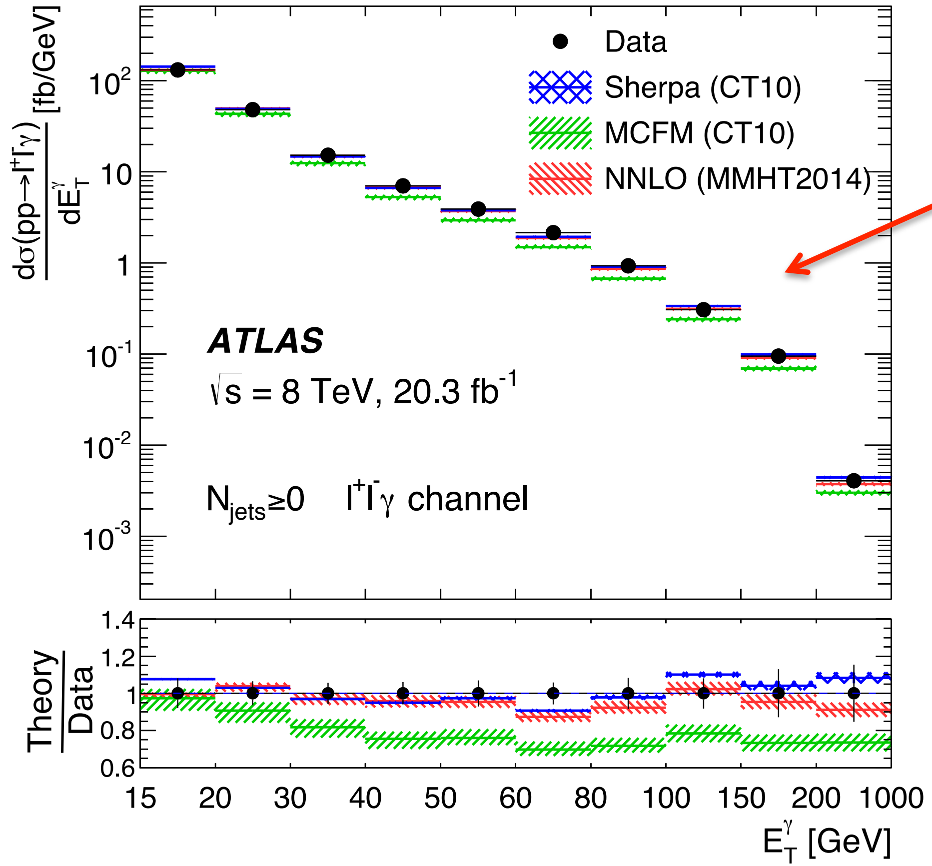
- Major backgrounds (Z/W+jets, γ +jets) determined with data driven methods

- Compare measurements to SM theory calculations at NNLO (arxiv:1504.01330)

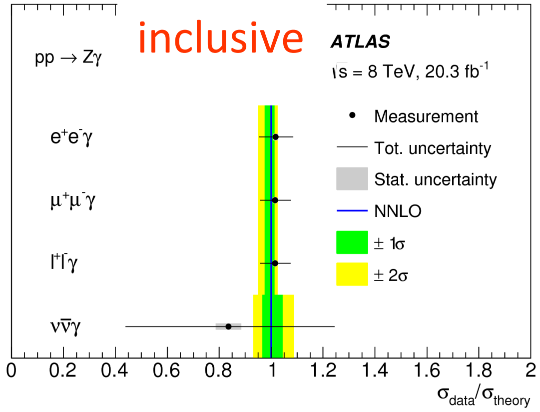
- Search for BSM sources of $Z \gamma$ production from aTGC's .

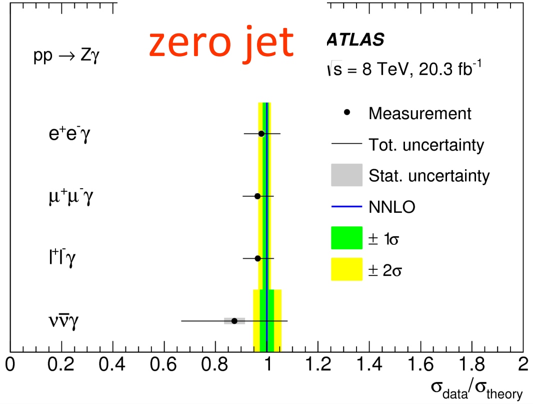
p + p → Z + γ + … at 8 TeV

arxiv:1604.05232



Compare unfolded differential spectra to SM Predictions (Sherpa+3 partons)



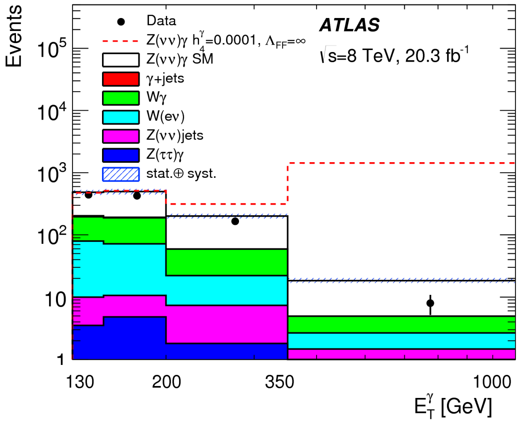


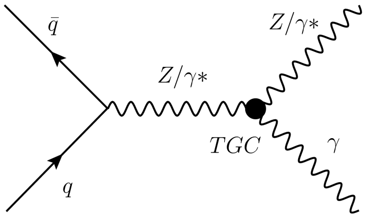
SM at NNLO ✔

p + p → Z + γ + … at 8 TeV

arxiv:1604.05232

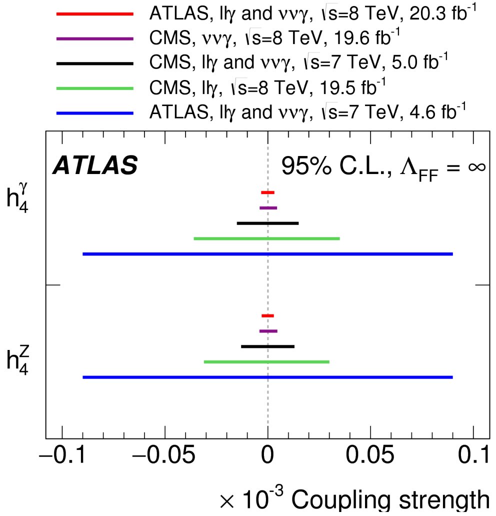
- Set aTGC limits on ZZγ and Zγγ using high Et photons

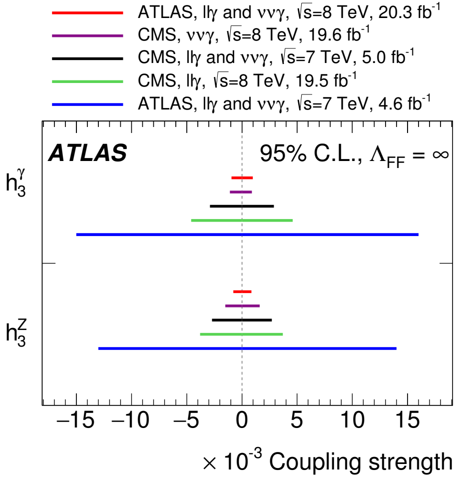




$h_i^V / \;(1 + \hat{s}/\Lambda_{FF}^2)^n$

with Λ = 4 TeV for uniterization

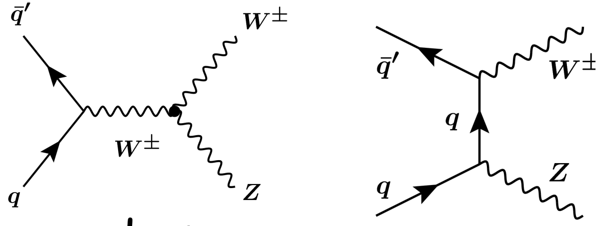




- The best constraints to date on h_i^V (i=3,4 V=γ, Z).

$p + p \rightarrow W^{\pm} + Z + \ldots$ at 8 TeV

arxiv:1603.02151

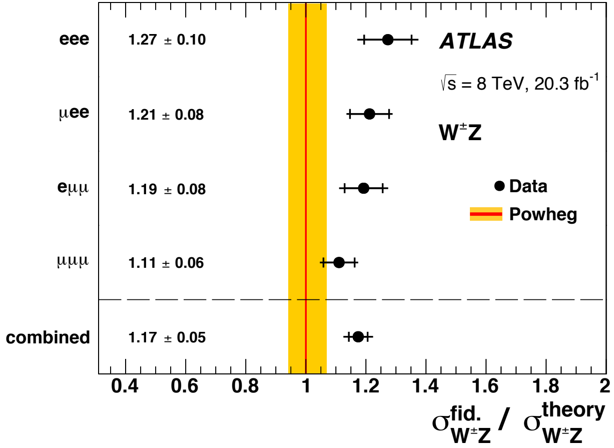


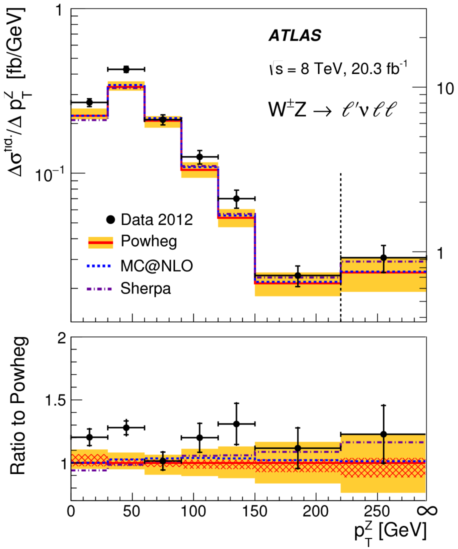
- Use W decays to $e\,\nu$ and $\mu\,\nu$, Z decays to $e^+ e^-$ and $\mu^+ \mu^-$ from 20.3 fb^{-1} of data.
- Event selected with at least one charged lepton with Et > 25 GeV,
- Backgrounds from Z+jets, Z+ γ, WW and top estimated from data driven methods; other EWK backgrounds from MC simulations.
- Total and differential cross sections measured for $66 < M(l^+ l^-) < 116$ GeV
- Precision of measurements require SM predictions beyond NLO. New (April 28, 2016) NNLO calculations now available: arXiv:1604.08576 .

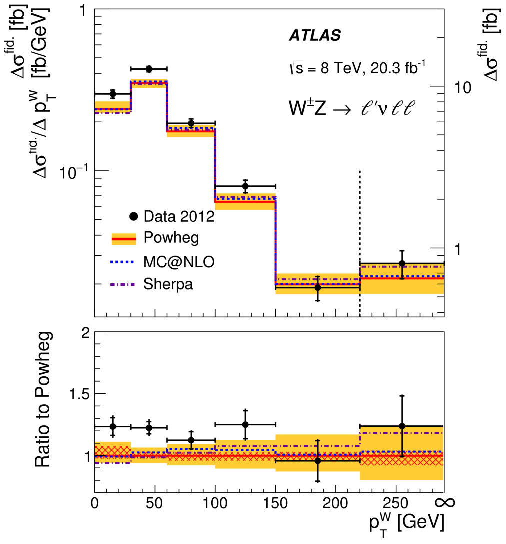
$p + p \rightarrow W^{\pm} + Z + \ldots$ at 8 TeV

arxiv:1603.02151

- NLO SM predictions (redline Powheg+Pythia) disagree with data.







$\sigma^{\text{fid.}}_{W^{\pm}Z\rightarrow\ell'\nu\ell\ell}$

Channel	$\sigma^{\text{fid.}}$ [fb]	$\delta_{\text{stat.}}$ [%]	$\delta_{\text{sys.}}$ [%]	$\delta_{\text{lumi.}}$ [%]	$\delta_{\text{tot.}}$ [%]
Combined	35.1	2.7	2.4	2.2	4.2
SM expectation	30.0	—	—	—	7.0

SM at NLO not OK.
➔ need for NNLO

$p + p \rightarrow W^{\pm} + Z + \ldots$ at 8 TeV

arxiv:1603.02151

- The WZ channel has an approximate radiation zero similar to that Wγ production and is therefore particularly sensitive to higher order QCD corrections (arXiv:1604.08576):

$\sqrt{s}$	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]	$\sigma_{\rm NLO}/\sigma_{\rm LO}$	$\sigma_{\rm NNLO}/\sigma_{\rm NLO}$
8	$13.654(1)\,^{+1.3\%}_{-2.1\%}$	$22.750(2)\,^{+5.1\%}_{-3.9\%}$	$24.690(16)\,^{+1.8\%}_{-1.9\%}$	$+66.6\%$	$+\ 8.5\%$

- Compare the NNLO prediction to the ATLAS 8 TeV WZ measurement with $66 < M(l^+ l^-) < 116$ GeV:

$\sqrt{s}$	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]	$\sigma_{\rm ATLAS}$ [pb]
8	$13.261(9)^{+1.3\%}_{-2.1\%}$	$22.03(2)^{+5.1\%}_{-3.9\%}$	$23.92(3)^{+1.7\%}_{-1.8\%}$	$24.3\,^{+0.6}_{-0.6}({\rm stat})^{+0.6}_{-0.6}({\rm syst})^{+0.5}_{-0.5}({\rm lumi})^{+0.4}_{-0.4}({\rm th})$

SM at NNLO ✔

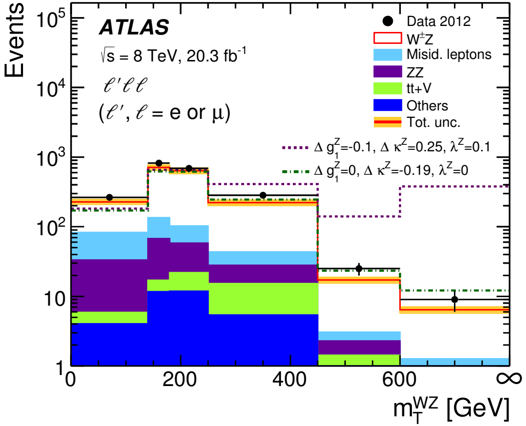
aTGC limits from p + p → $W^{\pm}$ + Z + … at 8 TeV

arxiv:1603.02151

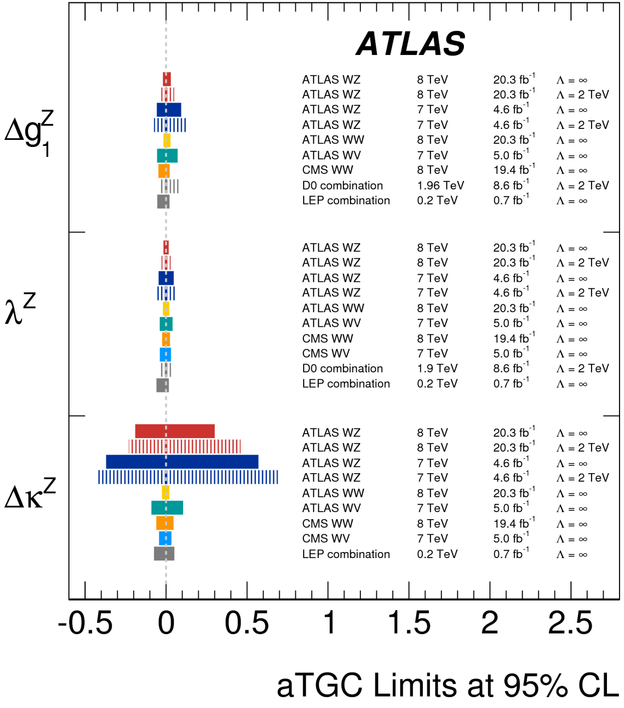
- Set aTGC limits on the WWZ coupling using the transverse mass of the WZ pair.

$$\mathcal{L} = ig_{WWV}\left[g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + k^V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\right]$$

$$\frac{\Delta g_1^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2} \qquad \frac{\Delta k^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2} \qquad \frac{\lambda^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$$



Combined WW and WZ measurements provide the best WWZ aTGC limits



$p + p \rightarrow W^{\pm} + Z + \ldots$ at 13 TeV

Approved today by ATLAS

- Use W decays to $e\,\nu$ and $\mu\,\nu$, Z decays to $e^+ e^-$ and $\mu^+ \mu^-$ from 3.2 fb^{-1} of data.

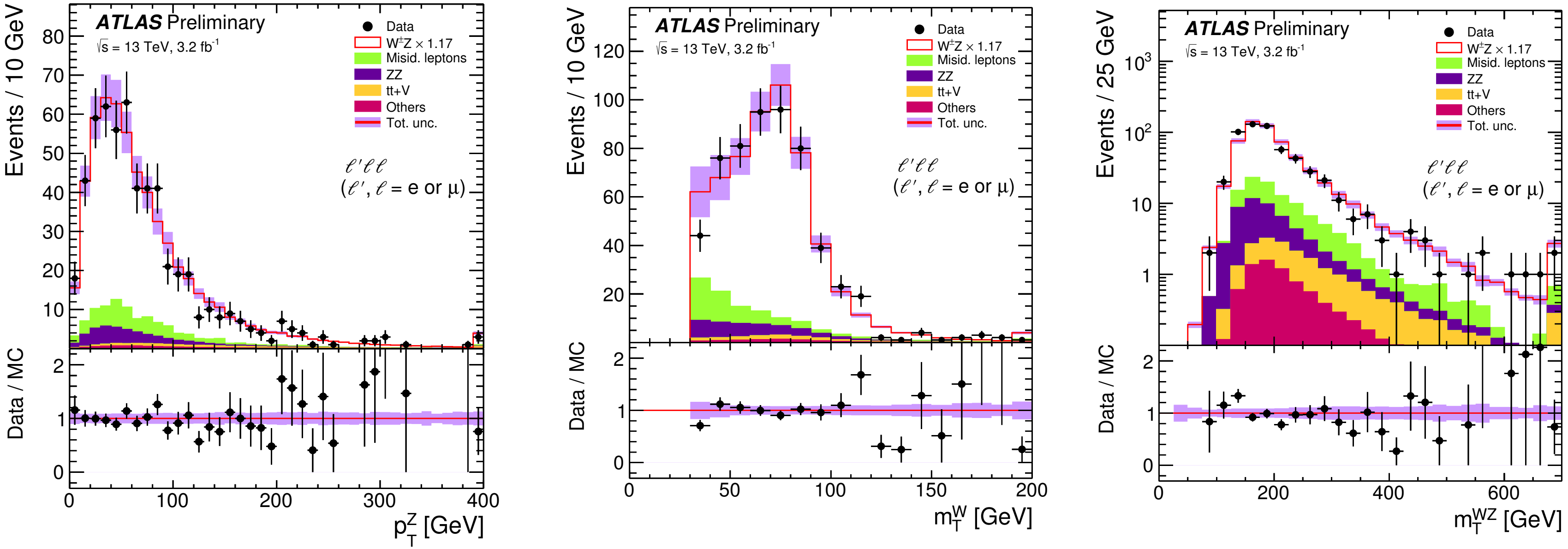
- Event selected with at least one charged lepton with Et > 25 GeV,

- Backgrounds from Z+jets, $Z+\gamma$, WW and top estimated from data driven methods; other EWK backgrounds from MC simulations.

- Total cross sections measured for $66 < M(l^+ l^-) < 116$ GeV

$p + p \rightarrow W^{\pm} + Z + \ldots$ at 13 TeV

Approved today by ATLAS

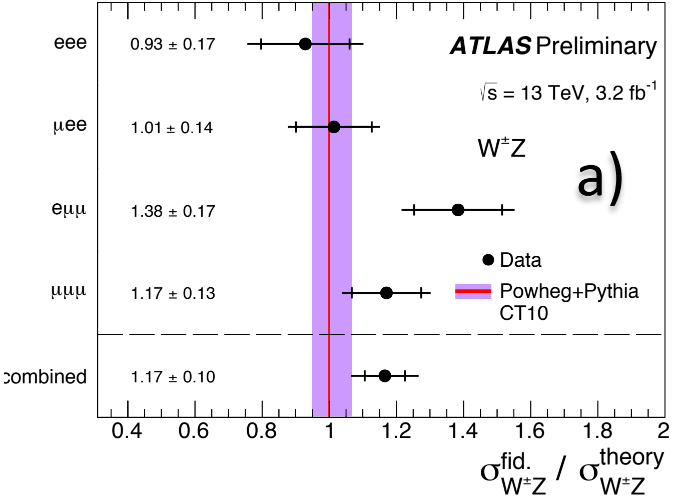


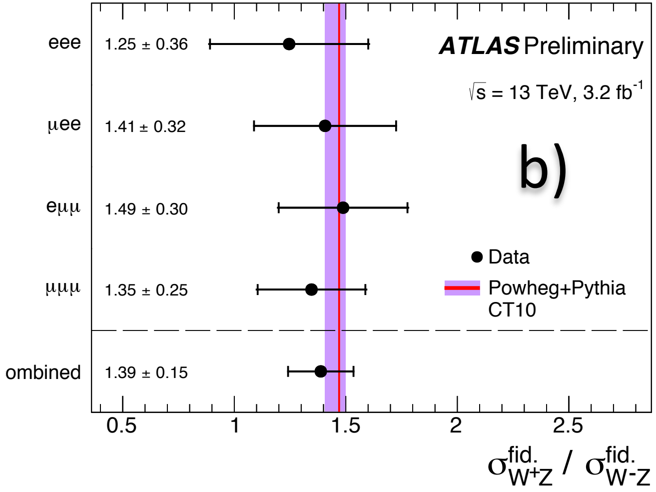
- Detector-level data (points with uncertainties). The solid red curve is the total background plus SM WZ signal with uncertainty indicated by the shaded violet band.

  The SM WZ signal is calculated at NLO from Powheg+Pythia scaled by 1.17 to match the data.

$p + p \rightarrow W^{\pm} + Z + \ldots$ at 13 TeV

Approved today by ATLAS





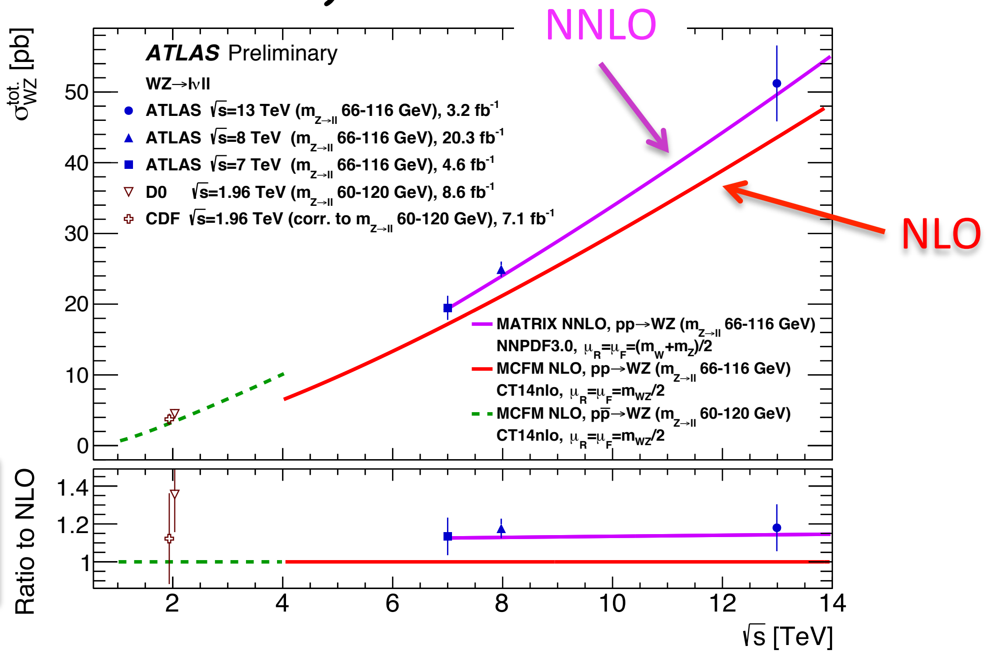
a) Ratio of measured WZ fiducial cross sections compared to NLO SM prediction from Powheg+Pythia with CT10 pdf.

b) Ratio of W^+Z/W^-Z fiducial cross sections compared to NLO SM prediction from Powheg+Pythia with CT10 pdf.

$p + p \rightarrow W^{\pm} + Z + \ldots$ at 13 TeV
Just aproved by ATLAS

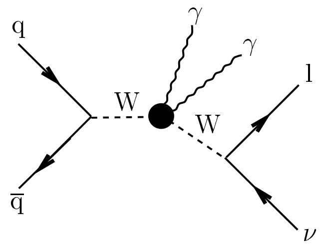
- Compare the ATLAS 13 TeV WZ measurement to the recent NNLO SM predictions (arXiv:1604.08576).

$\sqrt{s}$	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
7	$11.028(8)^{+0.5\%}_{-1.2\%}$	$17.93(1)^{+5.3\%}_{-4.1\%}$	$19.34(3)^{+1.6\%}_{-1.8\%}$
8	$13.261(9)^{+1.3\%}_{-2.1\%}$	$22.03(2)^{+5.1\%}_{-3.9\%}$	$23.92(3)^{+1.7\%}_{-1.8\%}$
13	$24.79(2)^{+4.2\%}_{-5.2\%}$	$44.67(3)^{+4.9\%}_{-3.9\%}$	$49.62(6)^{+2.2\%}_{-2.0\%}$



SM at NNLO ✔

Tri-boson production at ATLAS and QGC's



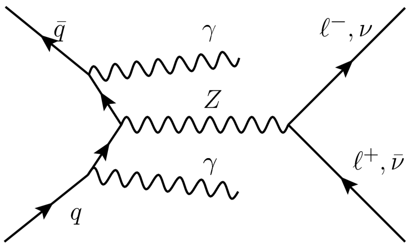
	$WWWW$	$WWZZ$	$ZZZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

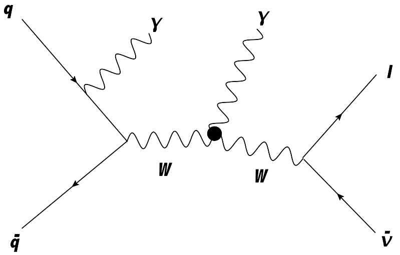
$p + p \rightarrow Z + \gamma + \gamma$ … at 8 TeV

arxiv:1604.05232

$p + p \rightarrow W + \gamma + \gamma$ … at 8 TeV

arxiv:1503.03243

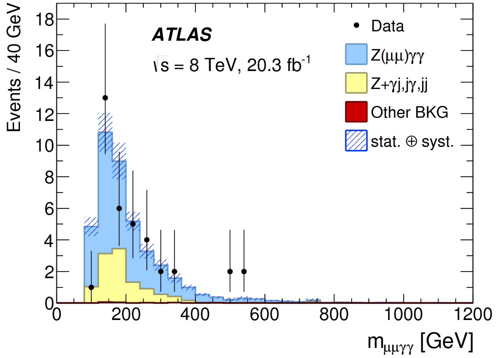


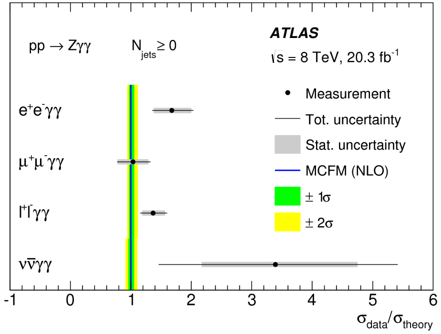


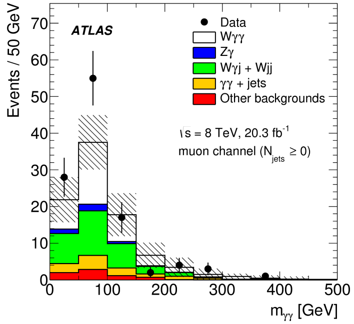
- Select W/Z leptonic decays from 20.3 fb^{-1} of data.
- For $Z\gamma\gamma$ photons with $E_T(\gamma) > 15$ GeV and $\Delta R(l\text{-}\gamma) > 0.4$
  For $W\gamma\gamma$ photons with $E_T(\gamma) > 20$ GeV and $\Delta R(l\text{-}\gamma) > 0.7$
- Compare measurements to SM theory calculations at NLO using MCFM.
- Search for BSM sources of $Z\gamma\gamma$ /$W\gamma\gamma$ production from aQGC's .

p + p → Z + γ + γ … at 8 TeV
arxiv:1604.05232

p + p → W + γ + γ … at 8 TeV
arxiv:1503.03243







	$\sigma^{\rm fid}$ [fb]	$\sigma^{\rm MCFM}$ [fb]
Inclusive ($N_{\rm jet} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\rm jet} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

- Observation of Zγγ signal with significance at the level 5 sigma.
- Evidence for Wγγ with significance at the level 3 sigma.
- Within large data statistical uncertainties we find agreement with SM predictions at NLO using MCFM.

SM at NLO ✔

p + p → Z + γ + γ … at 8 TeV
arxiv:1604.05232

p + p → W + γ + γ … at 8 TeV
arxiv:1503.03243

- Use the M(γγ) spectrum to set aQGC limits:
  M(γγ) > 200 [300] GeV for $Z(l^+ l^-)+\gamma\gamma$ [Z(νν)+γγ]: M(γγ) > 300 GeV for W+γγ
- Choose some parameters describing dimension 8 operators:

$$\mathcal{L}_{M,2} = \frac{f_{M2}}{\Lambda^4}[B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\phi)^\dagger D^\beta\phi]$$

$$\mathcal{L}_{M,3} = \frac{f_{M3}}{\Lambda^4}[B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\phi)^\dagger D^\mu\phi]$$

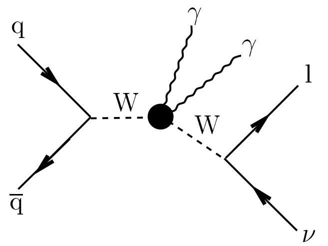
$$\mathcal{L}_{T,0} = \frac{f_{T0}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \mathrm{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}]$$

$$\mathcal{L}_{T,5} = \frac{f_{T5}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta}$$

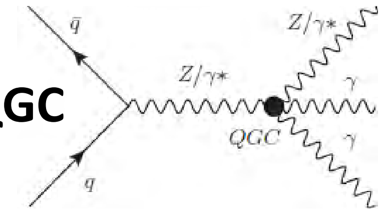
$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4}B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

unitarization

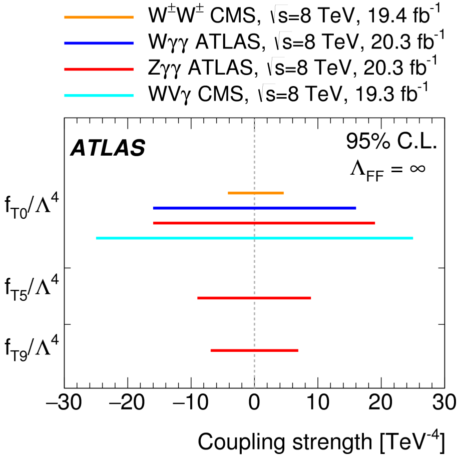
$$f \to \left(1 + \frac{s}{\Lambda_{\mathrm{FF}}^2}\right)^{-n} \times f.$$



aQGC



- WWγγ and ZZγγ sensitive to f_{M2} and f_{M2}
  WWγγ , ZZγγ and Zγγγ sensitive to f_{T0} and f_{T5}
  ZZγγ and Zγγγ sensitive to f_{T0}



(using convention of Eboli et al.)

$p + p \rightarrow Z + \gamma + \gamma$ … at 8 TeV
arxiv:1604.05232

n	Λ_{FF} [TeV]	Limits 95% C.L.	Observed [TeV^{-4}]	Expected [TeV^{-4}]
0	∞	f_{M2}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.2, 1.2] \times 10^4$
		f_{M3}/Λ^4	$[-2.9, 2.7] \times 10^4$	$[-2.2, 2.2] \times 10^4$
		f_{T0}/Λ^4	$[-0.86, 1.03] \times 10^2$	$[-0.65, 0.82] \times 10^2$
		f_{T5}/Λ^4	$[-0.69, 0.68] \times 10^3$	$[-0.52, 0.52] \times 10^3$
		f_{T9}/Λ^4	$[-0.74, 0.74] \times 10^4$	$[-0.58, 0.59] \times 10^4$
2	5.5	f_{M2}/Λ^4	$[-1.8, 1.9] \times 10^4$	$[-1.4, 1.5] \times 10^4$
	5.0	f_{M3}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.6] \times 10^4$
	0.7	f_{T0}/Λ^4	$[-2.3, 2.1] \times 10^3$	$[-1.9, 1.6] \times 10^3$
	0.6	f_{T5}/Λ^4	$[-2.3, 2.2] \times 10^4$	$[-1.8, 1.8] \times 10^4$
	0.4	f_{T9}/Λ^4	$[-0.89, 0.86] \times 10^6$	$[-0.71, 0.68] \times 10^6$

$p + p \rightarrow W + \gamma + \gamma$ … at 8 TeV
arxiv:1503.03243

		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	$[-2.9,\ 2.5] \times 10^5$	$[-3.7,\ 3.3] \times 10^5$

Λ_{FF} = 600 GeV for f_{T0}

Λ_{FF} = 500 GeV for f_{M2} and f_{M3}

(using convention from VBFNLO)

WWγγ ZZγγ Zγγγ aQGC consistent with 0

SM ✔

Summary

- The ATLAS (and CMS) collaboration are making measurements of the production of two EWK bosons in pp collisions at 7, 8 and recently 13 TeV. Tri-boson production is just now being detected.
- The theory community is keeping pace with the required SM theory predictions for di-boson production with QCD corrections at order α_s^2.
- Measurements and SM theory agree at these new levels of precision.
- Testing the triple and quartic gauge couplings are putting stringent limits on the phase space of postulated anomalous-coupling parameters.
- The advent of high statistics 13 TeV data will continue to increase the precision of multi-boson measurements, requiring new QCD+EWK calculations for testing the validity (or violation) of SM triple and quartic gauge-coupling.

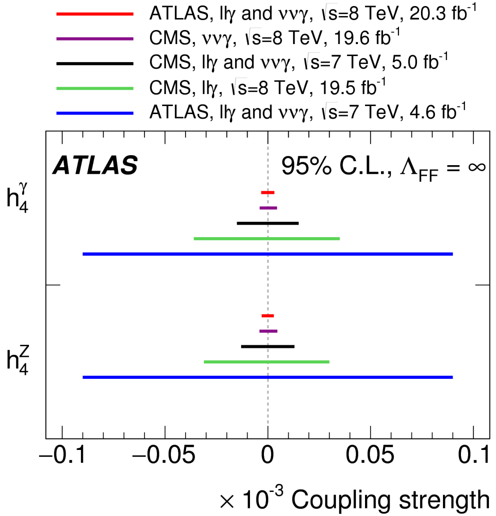
Additional Information

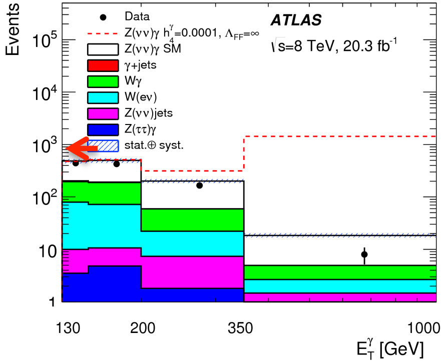
p + p → Z + γ + … at 8 TeV

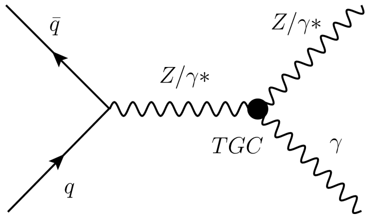
[arxiv:1604.05232](https://arxiv.org/abs/1604.05232)

- Set aTGC limits on ZZγ and Zγγ using high Et photons

Process	$pp \to \ell^+\ell^-\gamma$ and $pp \to \nu\bar{\nu}\gamma$	
Λ_{FF}	∞	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-9.5, 9.9] \times 10^{-4}$	$[-1.8, 1.8] \times 10^{-3}$
h_3^Z	$[-7.8, 8.6] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-3}$
h_4^γ	$[-3.2, 3.2] \times 10^{-6}$	$[-6.0, 5.9] \times 10^{-6}$
h_4^Z	$[-3.0, 2.9] \times 10^{-6}$	$[-5.5, 5.4] \times 10^{-6}$
Λ_{FF}	4 TeV	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-1.6, 1.7] \times 10^{-3}$	$[-3.0, 3.1] \times 10^{-3}$
h_3^Z	$[-1.3, 1.4] \times 10^{-3}$	$[-2.5, 2.6] \times 10^{-3}$
h_4^γ	$[-1.2, 1.1] \times 10^{-5}$	$[-2.2, 2.1] \times 10^{-5}$
h_4^Z	$[-1.0, 1.0] \times 10^{-5}$	$[-1.9, 1.9] \times 10^{-5}$







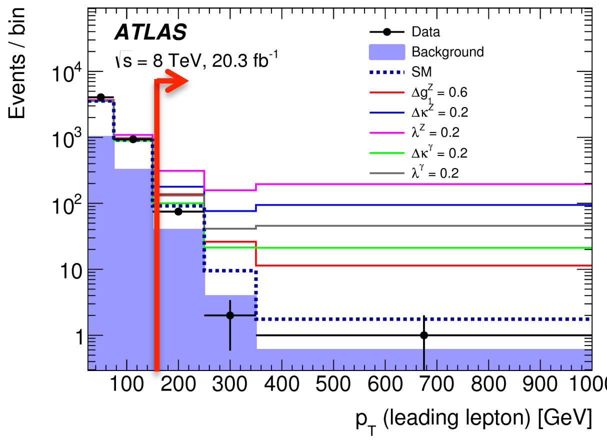
$h_i^V / (1 + \hat{s}/\Lambda_{FF}^2)^n$

- The best aTGC constraints to date on h_i^V (i=3,4 V=γ,Z)

ZZγ and Zγγ TGC consistent with 0 SM ✔

$p + p \rightarrow W^{\pm} + W^{\mp} + \ldots$ at 8 TeV

arxiv:1603.01702



- Set aTGC limits on ZWW and γWW couplings using the leading lepton in the e/μ final states.

$$\mathcal{L} = ig_{WWV}\left[g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + k^V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\right]$$

- Limits on $\frac{\Delta g_1^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$ $\frac{\Delta k^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$ $\frac{\lambda^V}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$ (V = Z, γ)

Scenario	Parameter	Expected	Observed	Expected	Observed
		$\Lambda = \infty$		$\Lambda = 7$ TeV	
No constraints scenario	Δg_1^Z	[−0.498, 0.524]	[−0.215, 0.267]	[−0.519, 0.563]	[−0.226, 0.279]
	Δk^Z	[−0.053, 0.059]	[−0.027, 0.042]	[−0.057, 0.064]	[−0.028, 0.045]
	λ^Z	[−0.039, 0.038]	[−0.024, 0.024]	[−0.043, 0.042]	[−0.026, 0.025]
	Δk^γ	[−0.109, 0.124]	[−0.054, 0.092]	[−0.118, 0.136]	[−0.057, 0.099]
	λ^γ	[−0.081, 0.082]	[−0.051, 0.052]	[−0.088, 0.089]	[−0.055, 0.055]

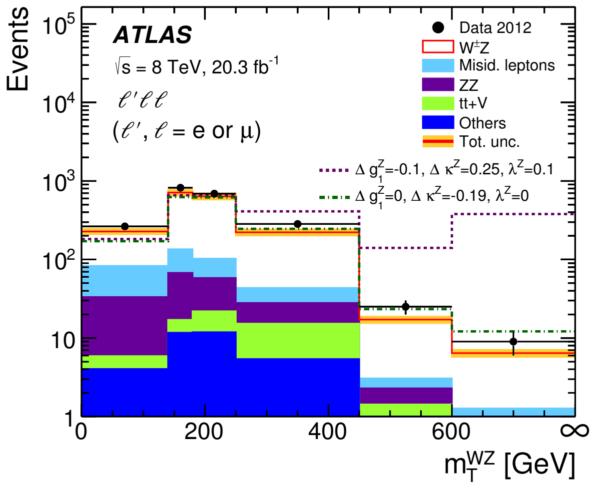
ZWW and γWW aTGC consistent with 0 SM ✔

- Limits comparable to or better than previous ATLAS measurements.

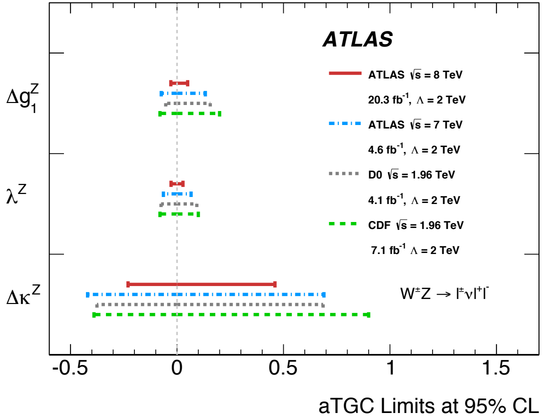
$p + p \rightarrow W^{\pm} + Z + \ldots$ at 8 TeV

arxiv:1603.02151

- Set aTGC limits on the ZWW coupling using the transverse mass of the WZ pair. Same parameterization as for WW on page 13.



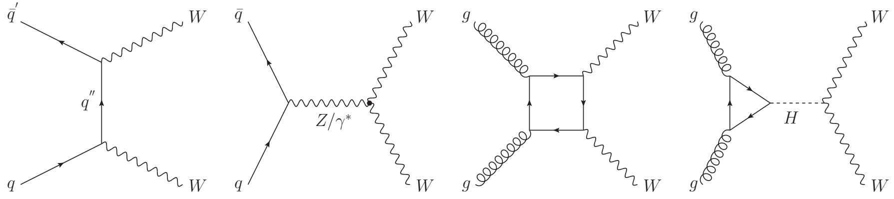
Λ_{co}	Coupling	Expected	Observed
2 TeV	Δg_1^Z	[−0.023 ; 0.055]	[−0.029 ; 0.05(
	$\Delta\kappa^Z$	[−0.22 ; 0.36]	[−0.23 ; 0.46]
	λ^Z	[−0.026 ; 0.026]	[−0.028 ; 0.02ε
15 TeV	Δg_1^Z	[−0.016 ; 0.033]	[−0.019 ; 0.029
	$\Delta\kappa^Z$	[−0.17 ; 0.25]	[−0.19 ; 0.30]
	λ^Z	[−0.016 ; 0.016]	[−0.017 ; 0.01;
∞	Δg_1^Z	[−0.016 ; 0.032]	[−0.019 ; 0.029
	$\Delta\kappa^Z$	[−0.17 ; 0.25]	[−0.19 ; 0.30]
	λ^Z	[−0.016 ; 0.016]	[−0.016 ; 0.016

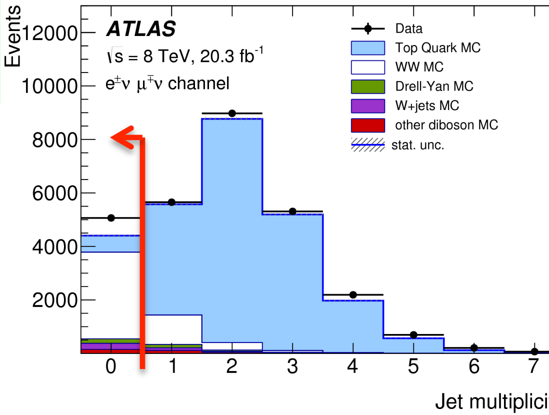


ZWW aTGC consistent with 0 SM ✔

$p + p \rightarrow W^{\pm} + W^{\mp} + \ldots$ at 8 TeV

arxiv:1603.01702





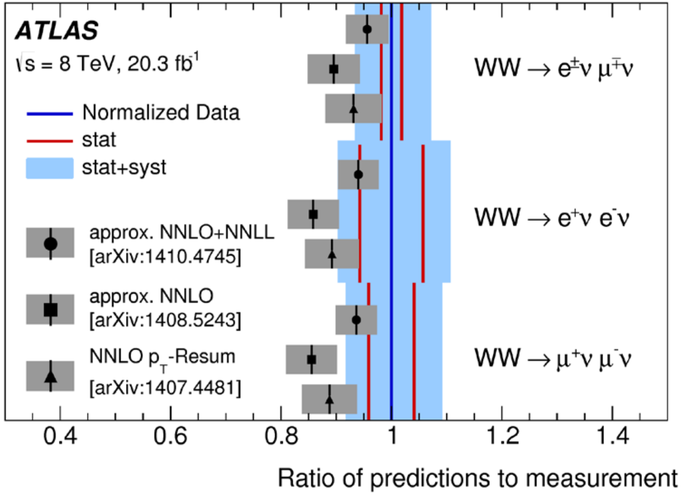
- Use W leptonic decays to $e\nu$, $\mu\nu$ from 20.3 fb^{-1} of data.
- Accept events if no jets with $E_T > 25$ GeV within $|\eta| < 4.5$.
- Backgrounds from W+jets, Drell-Yan, top, multi-jets data-driven; Diboson (WZ, ZZ W/Zγ) from MC
- SM theory calculations at NNLO

  arXiv:1408.5243 [hep-ph] and arXiv:1307.1347 [hep-ph]

$p + p \rightarrow W^{\pm} + W^{\mp} + \ldots$ at 8 TeV

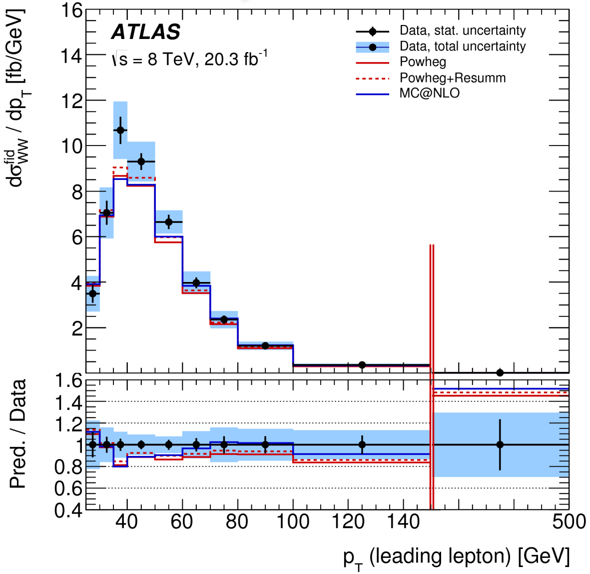
arxiv:1603.01702

Total WW Cross sections compared to SM



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

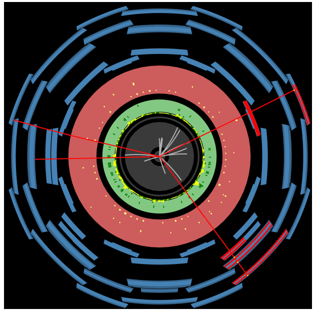
Unfolded differential spectra



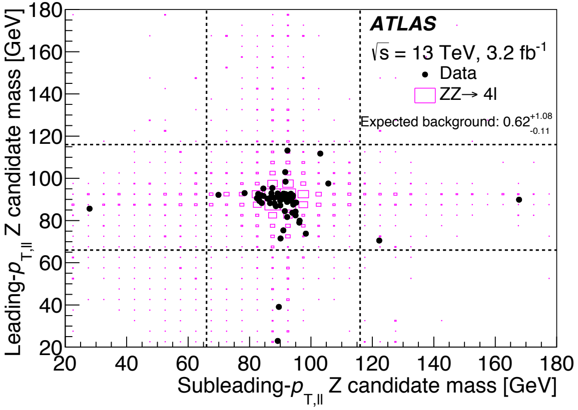
SM at NNLO ~ ✔

$p + p \rightarrow Z + Z + \ldots$ at 13 TeV

arxiv:1512.05314

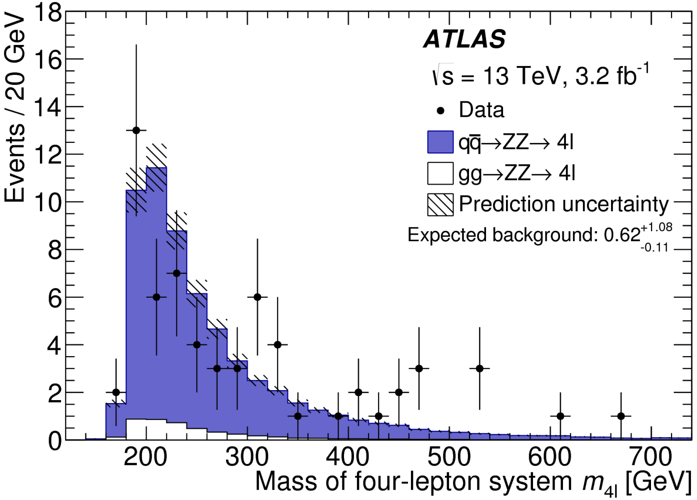


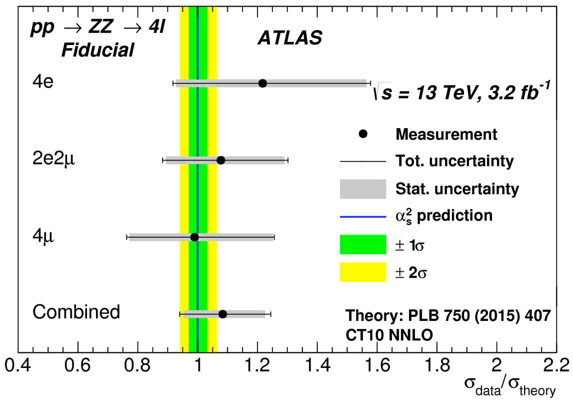
- Use Z decays to $e^+ e^-$ and $\mu^+ \mu^-$ from 3.2 fb^{-1} of data.
- Require leptons $P_T > 20$ GeV and M(l+l-) 66-116 GeV.
- A total of 63 events are observed with a total background of $0.62^{+1.08}_{-0.11}$` events.
- SM predictions at NNLO Phys. Lett. B750 (2015) 407–410 are compared to the measurement.

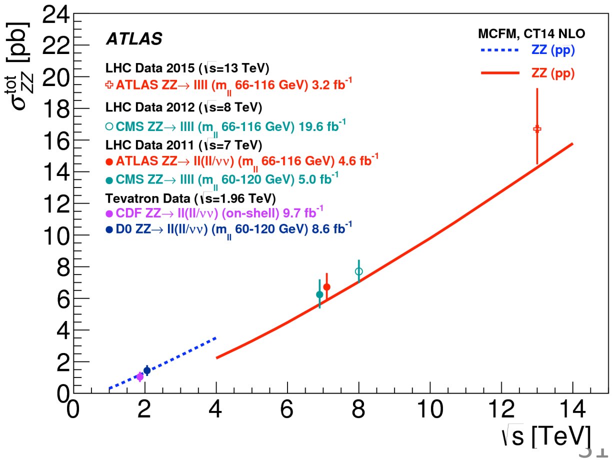


p + p → Z + Z + … at 13 TeV

arxiv:1512.05314







		$O(\alpha_S^2)$ prediction
σ_{ZZ}^{tot}	$16.7\ ^{+2.2}_{-2.0}\text{(stat.)}\ ^{+0.9}_{-0.7}\text{(syst.)}\ ^{+1.0}_{-0.7}\text{(lumi.)}$ pb	$15.6^{+0.4}_{-0.4}$ pb

SM at NNLO ✔