# Study of Multiboson Production with the ATLAS detector

#### Takashi Kubota (The University of Melbourne) on behalf of the ATLAS Collaboration

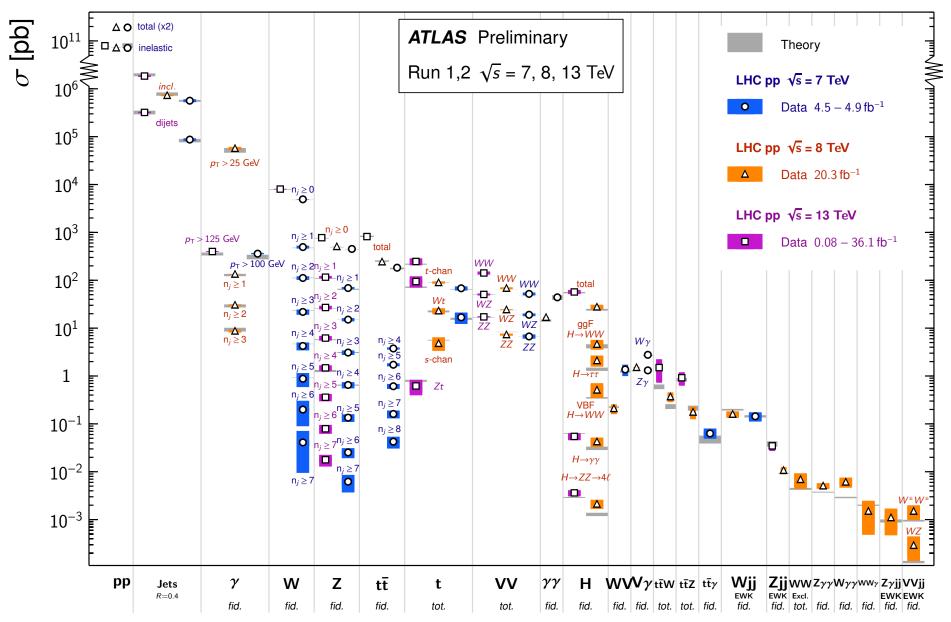
#### 31/08/2017 QCD@LHC 2017 @ Debrecen



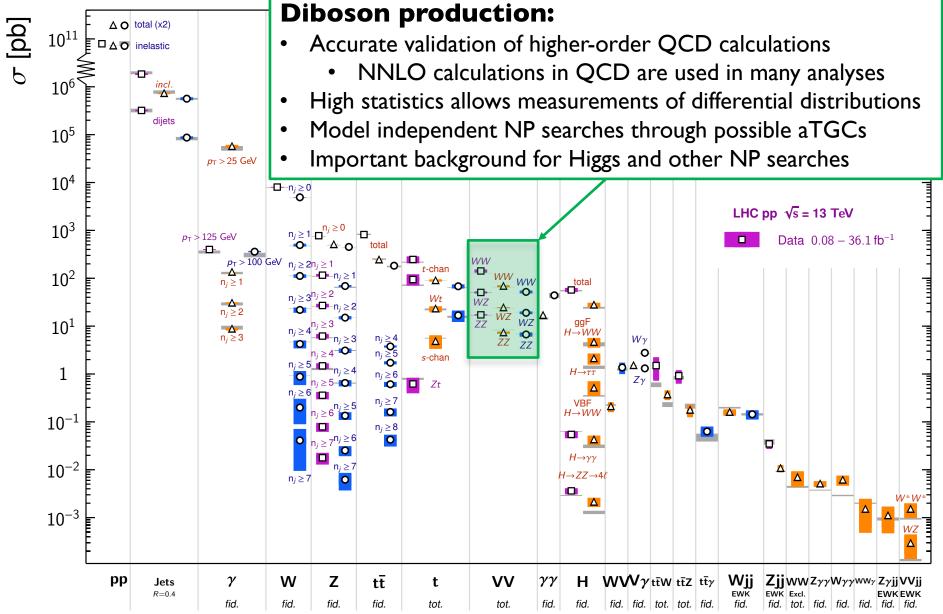




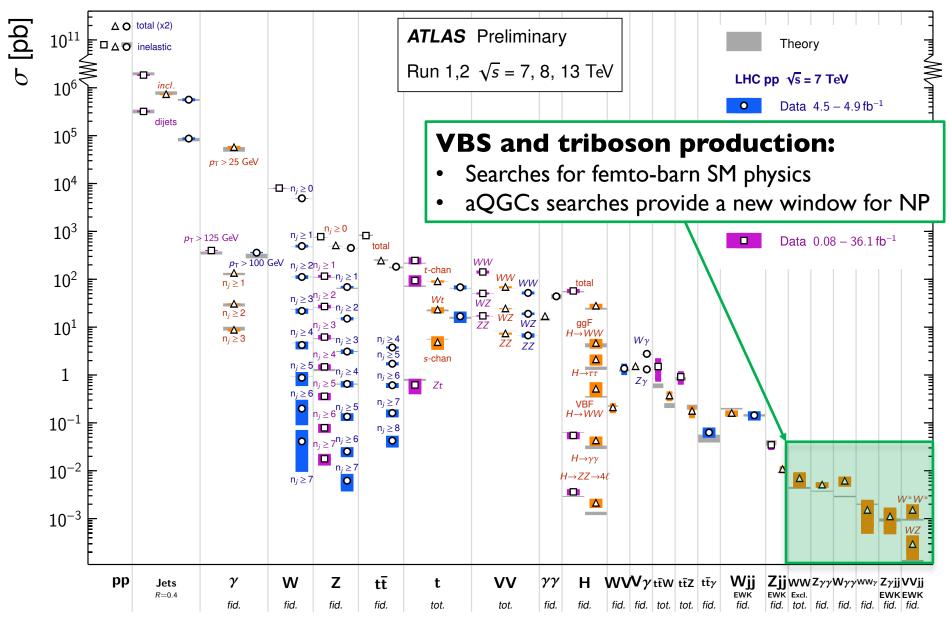
#### Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure



### Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure



#### Multiboson Production in ATLAS: Stringent Test of the Electroweak Structure



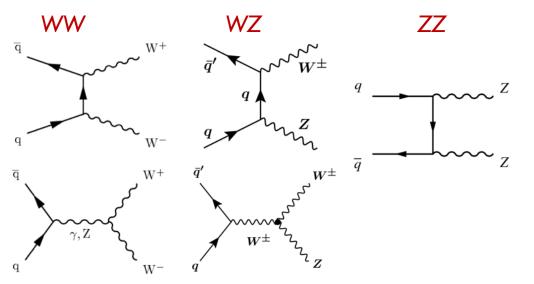
#### **Recent ATLAS multiboson measurements**

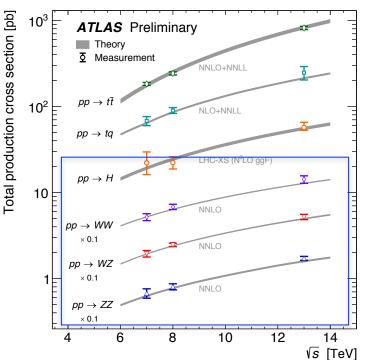
- Diboson Production
  - ZZ leptonic decay @ 13 TeV (<u>ATLAS-CONF-2017-031</u>)
  - WZ leptonic decay @ 13 TeV (<u>ATLAS-CONF-2016-043</u>, <u>Phys.Lett.B</u>
     <u>762 (2016)1</u>)
  - WW leptonic decay @ 13 TeV (<u>arXiv: 1702.04519</u>)
  - WW/WZ semi-leptonic decay @ 8 TeV (<u>arXiv: 1706.01702</u>)

- Vector Boson Scattering and triboson production
  - VBS Z $\gamma$ jj production @ 8 TeV (JHEP07(2017)107)
  - WVγ production @ 8 TeV (<u>arXiv: 1707.05597</u>)

### **Diboson measurements**

- WW, WZ and ZZ production
  - ZZ: smallest cross-section but clean  $4\ell$  signature : statistics dominant
  - WW: largest cross-section but difficult  $2\ell 2\nu$  final state: systematics dominant
  - WZ: nice balance
- First step are measurements of **full-leptonic** decay modes
  - I3 TeV results are published with all channels
- Then, analyses of **semi-leptonic** decay modes
  - More stat. gives us higher sensitivity to NP
  - 8 TeV result of WW/WZ production



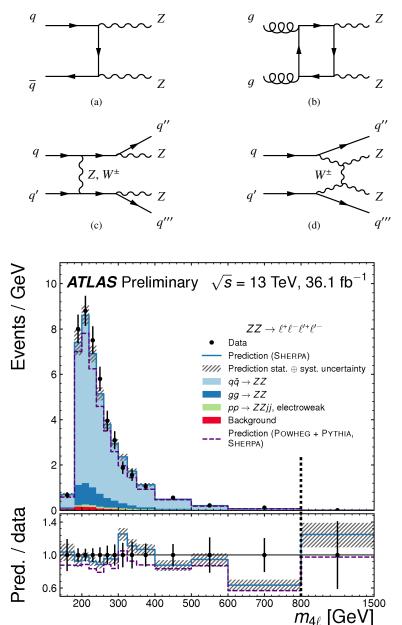


https://twiki.cern.ch/twiki/bin/view/

AtlasPublic/StandardModelPublicResults

6

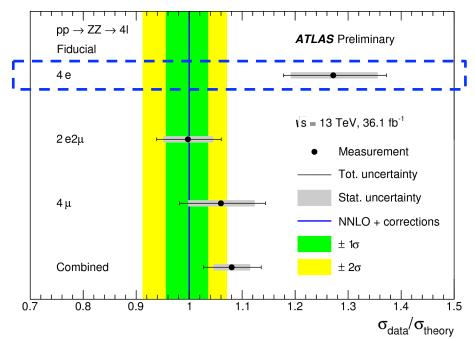
- $ZZ \rightarrow l^+ l^+ l^-$  signal (Nominal: Sherpa)
  - qq/gg processes are dominant
  - EW ZZjj (including VBS) is included
    - Also ZZV→I+I''-jj is included
- Compared two generators
  - Powheg: NLO ME calculation up to 1-jet
  - Sherpa: + LO ME calculation for 2, 3-jets
- 2 same-flavour opposite-sign e/ $\mu$  pairs
  - Only on-shell:  $66 < m_{\parallel} < 116 \text{ GeV}$
  - Main background: fake-lepton
  - Main systematics: lepton ID



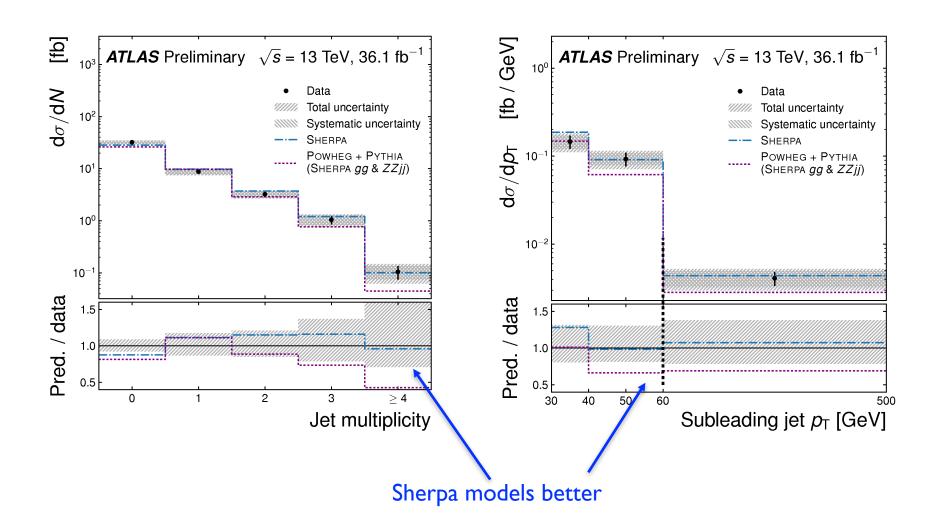
• Fiducial cross-section is measured with ~5% uncertainty (combined)

Channel	Measurement [fb]	Prediction [fb]
4e	$\begin{array}{c} 13.8^{+1.1}_{-1.0} \left[ \pm 0.9 \text{ (stat.) } \pm 0.3 \text{ (syst.) } ^{+0.5}_{-0.4} \text{ (lumi.)} \right] \\ 21.1^{+1.3}_{-1.2} \left[ \pm 1.0 \text{ (stat.) } ^{+0.5}_{-0.4} \text{ (syst.) } ^{+0.7}_{-0.6} \text{ (lumi.)} \right] \\ 11.5^{+0.9}_{-0.8} \left[ \pm 0.7 \text{ (stat.) } \pm 0.4 \text{ (syst.) } ^{+0.4}_{-0.3} \text{ (lumi.)} \right] \end{array}$	$10.9^{+0.5}_{-0.4}$
$2e2\mu$	$21.1^{+1.3}_{-1.2}$ [ $\pm 1.0$ (stat.) $^{+0.5}_{-0.4}$ (syst.) $^{+0.7}_{-0.6}$ (lumi.)]	$21.2^{+0.9}_{-0.8}$
$4\mu$	$11.5^{+0.9}_{-0.8} \left[\pm 0.7 \text{ (stat.) } \pm 0.4 \text{ (syst.) } ^{+0.4}_{-0.3} \text{ (lumi.)}\right]$	$10.9^{+0.5}_{-0.4}$
Combined	$46.4^{+2.4}_{-2.2}$ [ ± 1.5 (stat.) ±1.0 (syst.) $^{+1.5}_{-1.4}$ (lumi.)]	$42.9^{+1.9}_{-1.5}$

- Good agreement with MATRIX NNLO calculation
  - 2.7  $\sigma$  tension in 4e channel



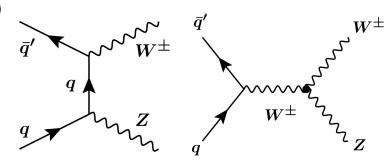
• 20 differential cross-sections are measured

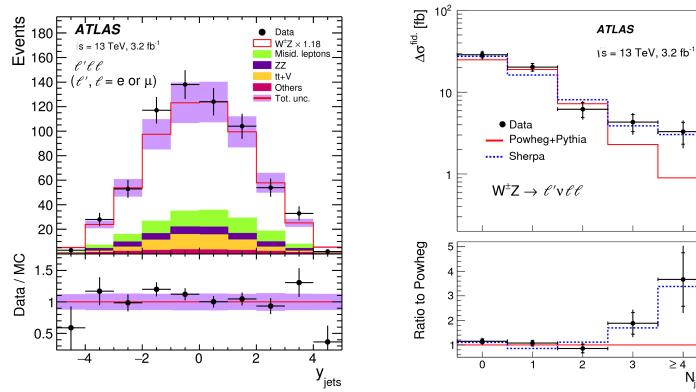


 $\mathsf{N}_{\mathsf{jets}}$ 

# WZ full-leptonic @ I3 TeV

- $WZ \rightarrow l'vl^+l^-$  signal (Nominal: Powheg+Pythia)
- Three high- $p_T$  e or  $\mu$ ٠
  - On-shell Z boson:  $|M_{\parallel} M_7| < 10 \text{ GeV}$
  - W boson selection:  $m_T^W > 30 \text{ GeV}$
- Main background: mis-identified leptons ۲
- Main systematics: Fake factor, lepton ID, luminosity ۲

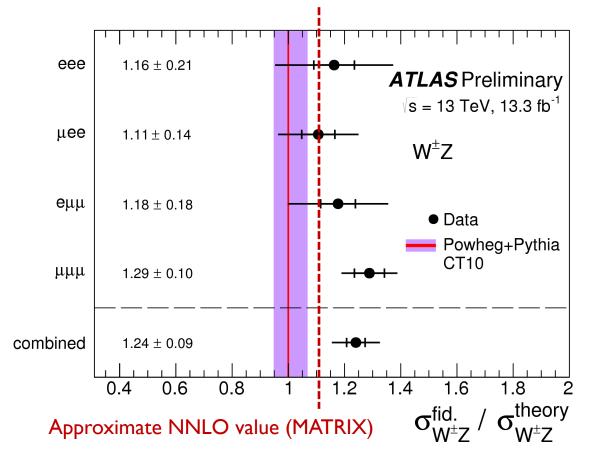




Fiducial cross-section measured with ~7% uncertainty

 $\sigma_{W^{\pm}Z \to \ell' \nu \ell \ell}^{\text{fid.}} = 66.2 \pm 1.8 \text{ (stat.)} \pm 3.6 \text{ (sys.)} \pm 2.1 \text{ (lumi.) fb.}$ 

- Good agreement with Powheg+Pythia prediction
  - Even better with approximate scale factor of 1.11 to MATRIX NNLO

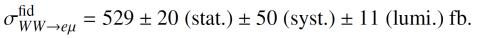


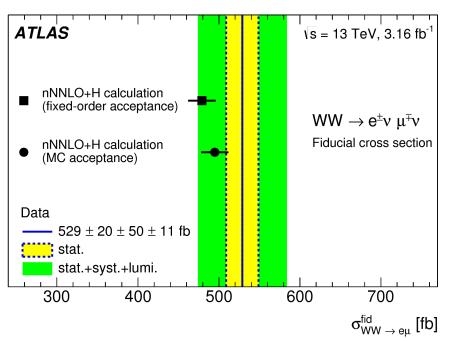
#### <u>arXiv: 1702.04519</u>

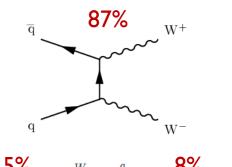
12

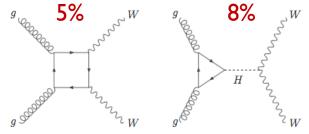
# WW full-leptonic @ I3 TeV

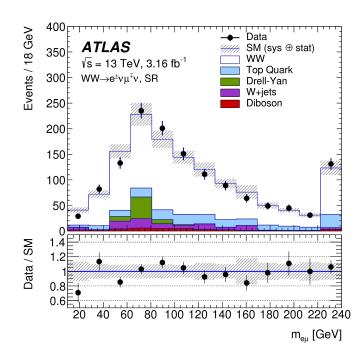
- WW $\rightarrow e v \mu v$  signal (nNNLO+H)
  - − qq → WW (Powheg norm. to O( $\alpha_S^2$ ))
  - − gg → WW (Sherpa norm. to  $O(\alpha_S^3)$ )
  - − gg → H → WW (Powheg norm. to  $O(\alpha_s^3)$ )
- High- $p_T e \mu$  pair with  $E_T^{miss}$  and no jet
  - Major systematics: Jet energy scale, fake factor
- Fiducial cross section measured with ~10% uncert.





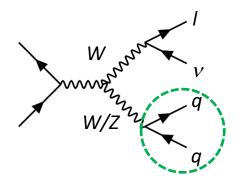


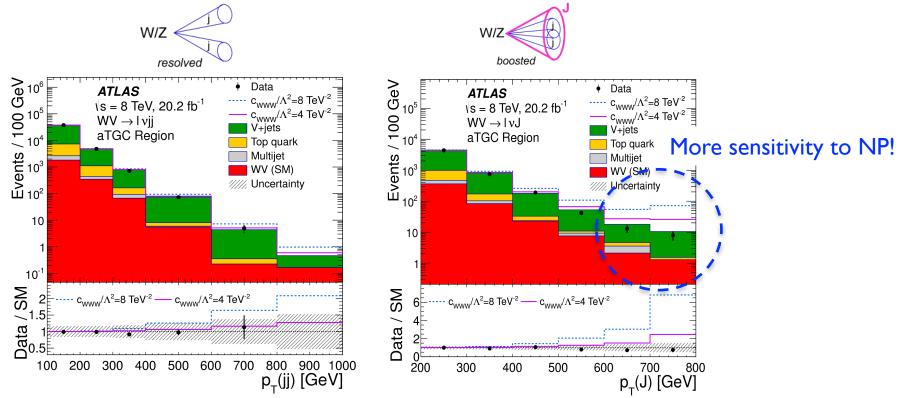




# WZ/WW semi-leptonic @ 8 TeV

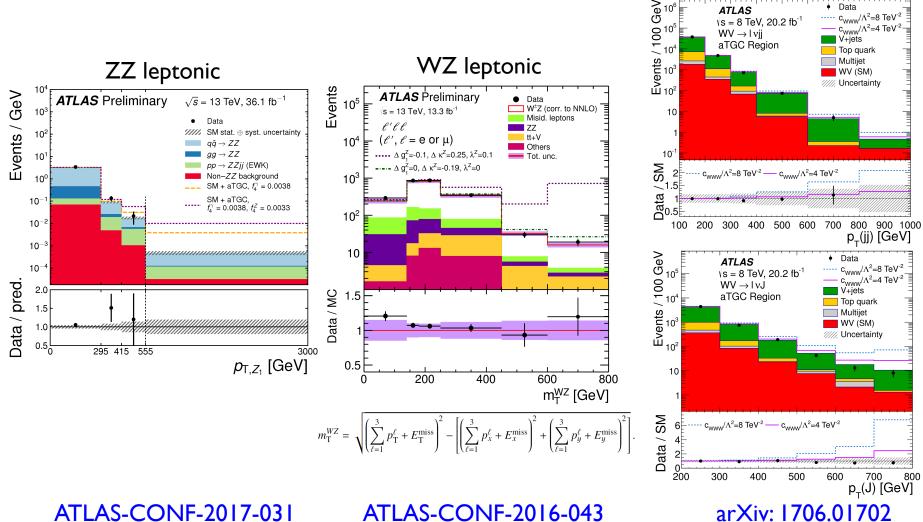
- Extend out sensitivity to NP
  - 6x BR than full-leptonic mode
  - Better kinematics reconstruction in WW
- Two jet reconstruction approaches
  - Resolved jet (Injj): two jets with anti-kt (R=0.4)
  - Boosted jet (InJ): one jet with anti-kt with R=1.0 and jet grooming





### **aTGC** search inputs

Extract constraints on aTGC parameters in high  $\hat{s}$  regions



ATLAS-CONF-2017-031

ATLAS-CONF-2016-043

WW/WZ semi-leptonic

Data

#### aTGC constraints

- Results with effective Lagrangian approach are shown
  - Results with EFT approach are also available

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

$$\frac{\mathcal{L}_{\mathrm{WWV}}}{g_{\mathrm{WWV}}} = (ig_1^{\mathrm{V}})(\mathrm{W}_{\mu\nu}^+ \mathrm{W}^{\mu} \mathrm{V}^{\nu} - \mathrm{W}_{\mu}^+ \mathrm{V}_{\nu} \mathrm{W}^{\mu\nu}) + (\kappa_{\mathrm{V}} \mathrm{W}_{\mu}^+ \mathrm{W}_{\nu} \mathrm{V}^{\mu\nu} + (i\lambda_{\mathrm{V}} \mathrm{W}_{\lambda\mu}^+ \mathrm{W}_{\nu}^\mu \mathrm{W}_{\nu}^\mu \mathrm{W}^{\nu}) + (i\lambda_{\mathrm{V}} \mathrm{W}_{\mu\nu}^+ \mathrm{W}_{\nu}^\mu \mathrm{W}_{\nu}^\mu \mathrm{W}_{\nu}^\mu \mathrm{W}_{\nu\nu}^\mu \mathrm{W$$

$$\bigcirc = 1 \text{ in SM}$$
$$\bigcirc = 0 \text{ in SM}$$

# $\mathcal{L}_{\rm ZZV} = -\frac{e}{M_Z^2} \left( f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right)$

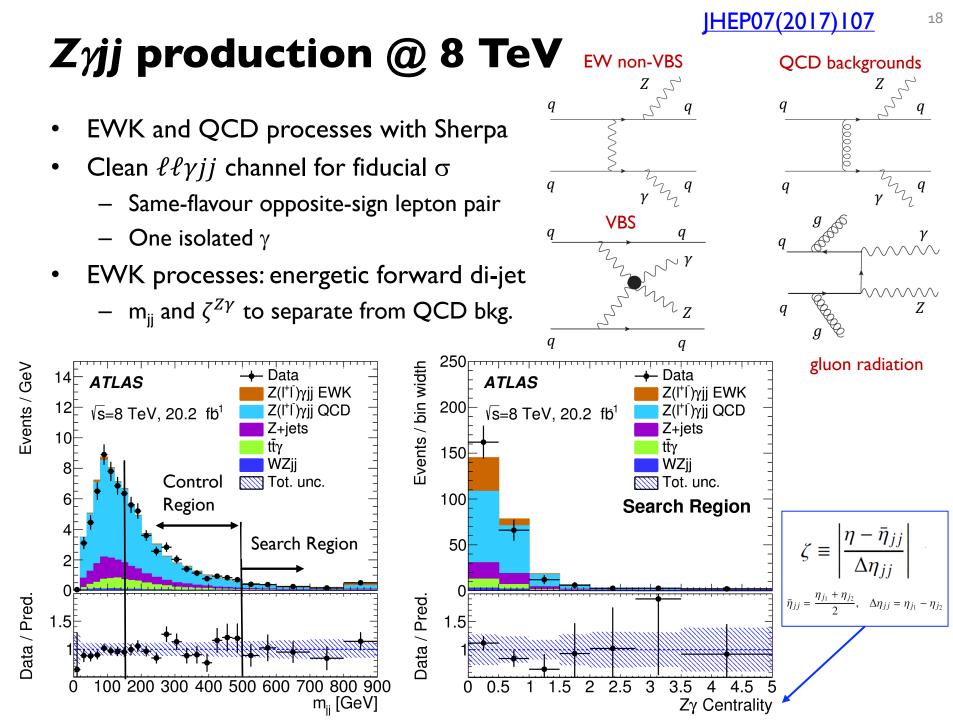
May 2017	CMS ATLAS ATLAS+CMS	<b>a</b> i i		(	_
	ATLAS+CMS	Channel	Limits	∫ <i>L</i> dt	√s
$f_4^{\gamma}$		ZZ (41,212v)	[-1.5e-02, 1.5e-02]	4.6 fb <sup>-1</sup>	7 TeV
<b>1</b> 4		ZZ (4I,2I2v)	[-3.8e-03, 3.8e-03]	20.3 fb <sup>-1</sup>	8 TeV
	_ <u> </u>	ZZ (4I)	[-1.8e-03, 1.8e-03]	36.1 fb <sup>-1</sup>	13 TeV
	<b>├</b> ────┥	ZZ (4I)	[-5.0e-03, 5.0e-03]	19.6 fb <sup>-1</sup>	8 TeV
	⊢	ZZ (2l2v)	[-3.6e-03, 3.2e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	<b>⊢−−−</b> 4	ZZ (4I,2I2v)	[-3.0e-03, 2.6e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	⊢	ZZ (4I)	[-1.3e-03, 1.3e-03]	35.9 fb <sup>-1</sup>	13 TeV
	<b>⊢</b>	ZZ (4I,2I2v)	[-1.0e-02, 1.0e-02]	9.6 fb <sup>-1</sup>	7 TeV
.7		ZZ (4I,2I2v)	[-1.3e-02, 1.3e-02]	4.6 fb <sup>-1</sup>	7 TeV
$f_4^Z$	<b>⊢−−−−</b>	ZZ (4I,2I2v)	[-3.3e-03, 3.2e-03]	20.3 fb <sup>-1</sup>	8 TeV
-	· · · · · · · · · · · · · · · · · · ·	ZZ (4I)	[-1.5e-03, 1.5e-03]	36.1 fb <sup>-1</sup>	13 TeV
	·	ZZ (4I)	[-4.0e-03, 4.0e-03]	19.6 fb <sup>-1</sup>	8 TeV
	<b>—</b>	ZZ (2l2v)	[-2.7e-03, 3.2e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
		ZZ (41,212v)	[-2.1e-03, 2.6e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	́ні́	ZZ (4I)	[-1.2e-03, 1.1e-03]	35.9 fb <sup>-1</sup>	13 TeV
	- · · ·	ZZ (41,212v)	[-8.7e-03, 9.1e-03]	9.6 fb <sup>-1</sup>	7 TeV
-2		ZZ (41,212v)	[-1.6e-02, 1.5e-02]	4.6 fb <sup>-1</sup>	7 TeV
$f_5^{\gamma}$	· • • • • • • • • • • • • • • • • • • •	ZZ (41,212v)	[-3.8e-03, 3.8e-03]	20.3 fb <sup>-1</sup>	8 TeV
5		ZZ (41)	[-1.8e-03, 1.8e-03]	36.1 fb <sup>-1</sup>	13 TeV
	······	ZZ (4I)	[-5.0e-03, 5.0e-03]	19.6 fb <sup>-1</sup>	8 TeV
	· • • • • • • • • • • • • • • • • • • •	ZZ(2l2v)	[-3.3e-03, 3.6e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	· · · · · · · · · · · · · · · · · · ·	ZZ(41,212v)	[-2.6e-03, 2.7e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	· ⊢ ·	ZZ (4I)	[-1.2e-03, 1.3e-03]	35.9 fb <sup>-1</sup>	13 TeV
	· · ·	ZZ (41,212v)	[-1.1e-02, 1.1e-02]	9.6 fb <sup>-1</sup>	7 TeV
7	· · ·	ZZ (4I,2I2v)	[-1.3e-02, 1.3e-02]	4.6 fb <sup>-1</sup>	7 TeV
$f_5^Z$	· · · · ·	ZZ (4I,2I2v)	[-3.3e-03, 3.3e-03]	20.3 fb <sup>-1</sup>	8 TeV
5		ZZ (41)	[-1.5e-03, 1.5e-03]	36.1 fb <sup>-1</sup>	13 TeV
	_ •	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb <sup>-1</sup>	8 TeV
	· '	ZZ (2l2v)	[-2.9e-03, 3.0e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	' <b></b> '	ZZ (41,212v)	[-2.2e-03, 2.3e-03]	24.7 fb <sup>-1</sup>	7,8 TeV
	' 🛶 '	ZZ (4I)	[-1.0e-03, 1.2e-03]	35.9 fb <sup>-1</sup>	13 TeV
		ZZ (41,212v)	[-9.1e-03, 8.9e-0β]	9.6 fb <sup>-1</sup>	7 TeV
				9.010	, C <b>v</b>
-0.0	2 0	0.02	0.04		0.06
	-		aTGC Li	mits @9	5% C.L

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

$$\frac{\mathcal{L}_{\mathrm{WWV}}}{g_{\mathrm{WWV}}} \neq ig_1^{\mathrm{V}} (\mathrm{W}_{\mu\nu}^+ \mathrm{W}^{\mu} \mathrm{V}^{\nu} - \mathrm{W}_{\mu}^+ \mathrm{V}_{\nu} \mathrm{W}^{\mu\nu}) + i\kappa_{\mathrm{V}} \mathrm{W}_{\mu}^+ \mathrm{W}_{\nu} \mathrm{V}^{\mu\nu} + \frac{i\lambda_{\mathrm{V}}}{m_{\mathrm{W}}^2} W_{\lambda\mu}^+ W_{\nu}^{\mu} \mathrm{V}^{\nu\lambda}$$

July 2017	CMS Central ATLAS Fit Value D0				
	LEP	Channel	Limits	∫ <i>L</i> dt	√s
A10	<b>⊢−−−</b>	WW	[-4.3e-02, 4.3e-02]	4.6 fb <sup>-1</sup>	7 TeV
$\Delta \kappa_{z}$	⊢	WW	[-2.5e-02, 2.0e-02]	20.3 fb <sup>-1</sup>	8 TeV
_	<b></b>	WW	[-6.0e-02, 4.6e-02]	<u>19.4</u> fb <sup>-1</sup>	8 TeV
		WZ	[-1.3e-01, 2.4e-01]	33.6 fb <sup>-1</sup>	8,13 TeV
		WZ	[-2.1e-01, 2.5e-01]	19.6 fb <sup>-1</sup>	8 TeV
		WV	[-9.0e-02, 1.0e-01]	4.6 fb <sup>-1</sup>	7 TeV
	· • • • • • • • • • • • • • • • • • • •	WV	[-4.3e-02, 3.3e-02]	5.0 fb <sup>-1</sup>	7 TeV
	i i i i i i i i i i i i i i i i i i i	WV	[-4.0e-02, 4.1e-02]	2.3 fb <sup>-1</sup>	13 TeV
	<u>⊢</u>	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb <sup>-1</sup>	0.20 TeV
2		WW	[-6.2e-02, 5.9e-02]	4.6 fb <sup>-1</sup>	7 TeV
λ <sub>z</sub>	· ⊢ ·	WW	[-1.9e-02, 1.9e-02]	20.3 fb <sup>-1</sup>	8 TeV
2		ww	[-4.8e-02, 4.8e-02]	4.9 fb <sup>-1</sup>	7 TeV
	' <b>⊢</b> ∎⊣'	ŴŴ	[-2.4e-02, 2.4e-02]	19.4 fb <sup>-1</sup>	8 TeV
		WZ	[-4.6e-02, 4.7e-02]	4.6_fb <sup>-1</sup>	7 TeV
	с	WZ	[-1.4e-02, 1.3e-02]	33.6 fb <sup>-1</sup>	8,13 TeV
	· · · · · · · · · · · · · · · · · · ·		[-1.8e-02, 1.6e-02]	19.6 fb <sup>-1</sup>	8 TeV
			[-3.9e-02, 4.0e-02]	4.6_fb <sup>-1</sup>	7 TeV
	· · · · · · · · · · · · · · · · · · ·	WV (lvjj)	[-2.2e-02, 2.2e-02]	20.2 fb <sup>-1</sup>	8 TeV
	······································	WV (lvJ)	[-1.3e-02, 1.3e-02]	20.2 fb <sup>-1</sup>	8 TeV
	· · · · · · · · · · · · · · · · · · ·		[-3.8e-02, 3.0e-02]	5.0 fb <sup>-1</sup>	7 TeV
	'H'	ŴV	[-1.1e-02, 1.1e-02]	19 fb <sup>-1</sup>	8 TeV
		ŴV	[-3.9e-02, 3.9e-02]	2.3 fb <sup>-1</sup>	13 TeV
		D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb <sup>-1</sup>	1.96 TeV
		LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb <sup>-1</sup>	0.20 TeV
7		WW	[-3.9e-02, 5.2e-02]	4.6 fb <sup>-1</sup>	7 TeV
$\Delta g_1^Z$		ww	[-1.6e-02, 2.7e-02]	20.3 fb <sup>-1</sup>	8 TeV
1		WW	[-9.5e-02, 9.5e-02]	4.9 fb <sup>-1</sup>	7 TeV
		ww	[-9.5e-02, 9.5e-02] [-4.7e-02, 2.2e-02]	4.9 lb 19.4 fb <sup>-1</sup>	8 TeV
			[-4.7e-02, 2.2e-02] [-5.7e-0 <u>2, 9.3</u> e-02]		
		WZ		4.6 fb <sup>-1</sup>	7 <u>TeV</u> 8,13 TeV
	· · · · · · · · · · · · · · · · · · ·	<u>WZ</u>	[-1.5e-02, 3.0e-02] [-1.8e-02, 3.5e-02]	33.6 fb <sup>-1</sup>	8 TeV
				19.6 fb <sup>-1</sup>	
		WV 	[-5.5e-02, 7.1e-02]	4.6 fb <sup>-1</sup>	- <u>7 TeV</u>
			[-2.7e-02, 4.5e-02]	20.2 fb <sup>-1</sup>	
	·	WV (lvJ)	[-2.1e-02, 2.4e-02]	20.2 fb <sup>-1</sup>	8 TeV
		- wv	[-8.7e-03, 2.4e-02]	19 fb <sup>-1</sup>	8 TeV
		WV	[-6.7e-02, 6.6e-02]	2.3 fb <sup>-1</sup>	13 TeV
		D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb <sup>-1</sup>	1.96 TeV
		LEP Comp.	[-5.4e-02, 2.1e-02]	0.7 fb <sup>-1</sup>	0.20 TeV
	0		0.5		1
			aTGC Li	mits @9	5% C.L.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



#### JHEP07(2017)107

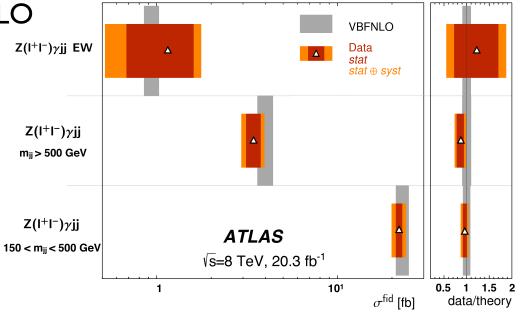
# *Ζγjj* production @ 8 TeV

• Fiducial cross-section measured with  $\ell \ell \gamma j j$ 

		• • • •	<b>~</b>
		cionit	ficance
_	U	JIZIIII	ICance
		0	

Channel	Phase-space	Process	Measured	Predicted
	$\operatorname{region}$	$\operatorname{type}$	cross-section [fb]	cross-section $[fb]$
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK	$1.1 \pm 0.5 \; (\text{stat}) \pm 0.4 \; (\text{syst})$	$0.94 \pm 0.09$
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK+QCD	$3.4 \pm 0.3 \text{ (stat)} \pm 0.4 \text{ (syst)}$	$4.0\pm0.4$
$Z(\ell^+\ell^-)\gamma jj$	Control region	EWK+QCD	$21.9 \pm 0.9 \text{ (stat)} \pm 1.8 \text{ (syst)}$	$22.9 \pm 1.9$

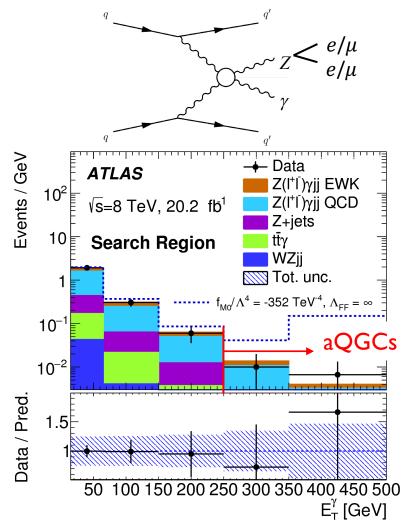
- Good agreement with VBFNLO
- Main uncertainties on  $\sigma_{\text{EW}}$ 
  - Statistical uncertainty: 40%
  - Jet energy scale: 36%
  - Sherpa modeling: 10%

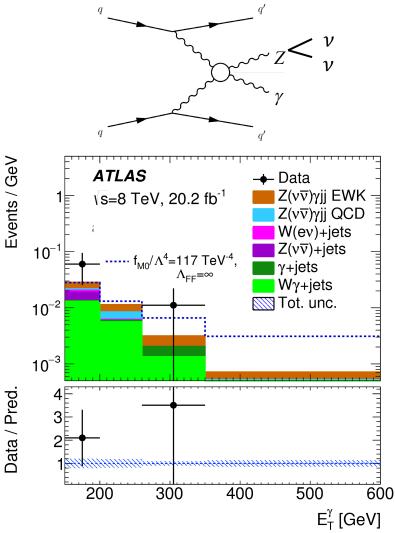


#### JHEP07(2017)107

# *Ζγjj* production @ 8 TeV

•  $E_{T}^{\gamma}$  distributions to constrain aQGCs are obtained both in  $\ell \ell \gamma j j$ and  $\nu \nu \gamma j j$  samples

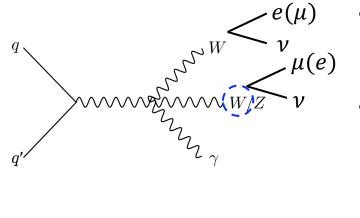




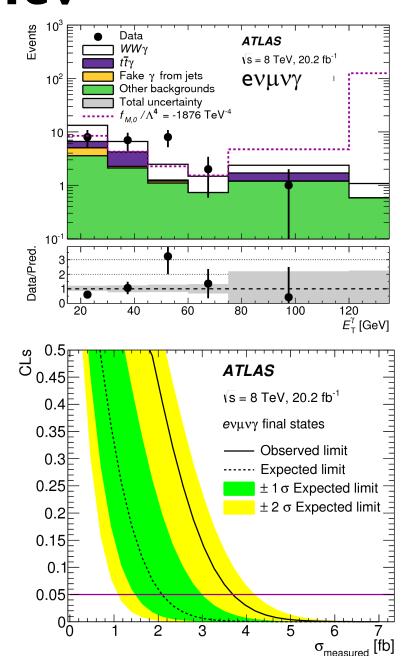
# WVγ production @ 8 TeV

-W/Z

 $\sim \sim \sim W$ 



- Modelled with Sherpa (LO + 1 parton)
- $ev\mu\nu\gamma$  channel
  - Opposite-sign  $e\mu$  pair
  - One isolated  $\gamma$
  - $E_{T}^{miss}$  from neutrinos
  - Only  $N_{jet} = 0$  bin
- Fiducial cross section
  - $-~\sigma_{\rm fid}$  = 1.5  $\pm$  0.9 (stat.)  $\pm$  0.5 (syst.) fb
    - 1.4  $\sigma$  significance
    - 2.0 fb (theory: VBFNLO)
  - Observed limit (95% CL): 3.7 fb
    - 2.1<sup>+0.9</sup><sub>-0.6</sub> fb (expected)

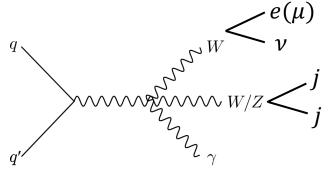


22

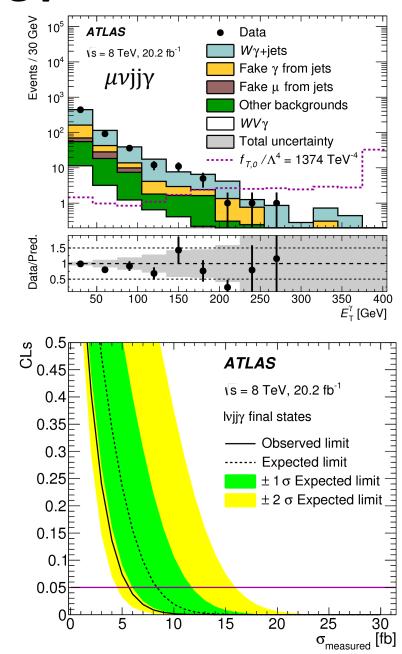
# WVγ production @ 8 TeV

W/Z

 $\bigvee \bigvee W$ 



- ℓνjjγ channel
  - One high- $p_T e \text{ or } \mu$
  - One isolated  $\gamma$
  - $E_{T}^{miss}$  from neutrinos
  - $-~\geq 2$  jet with 70 <  $m_{jj}$  < 100 GeV
- Fiducial cross section
  - Observed limit (95% CL): 6 fb
    - $8.4^{+3.4}_{-2.4}$  fb (expected: VBFNLO)
    - Most stringent limit to date!



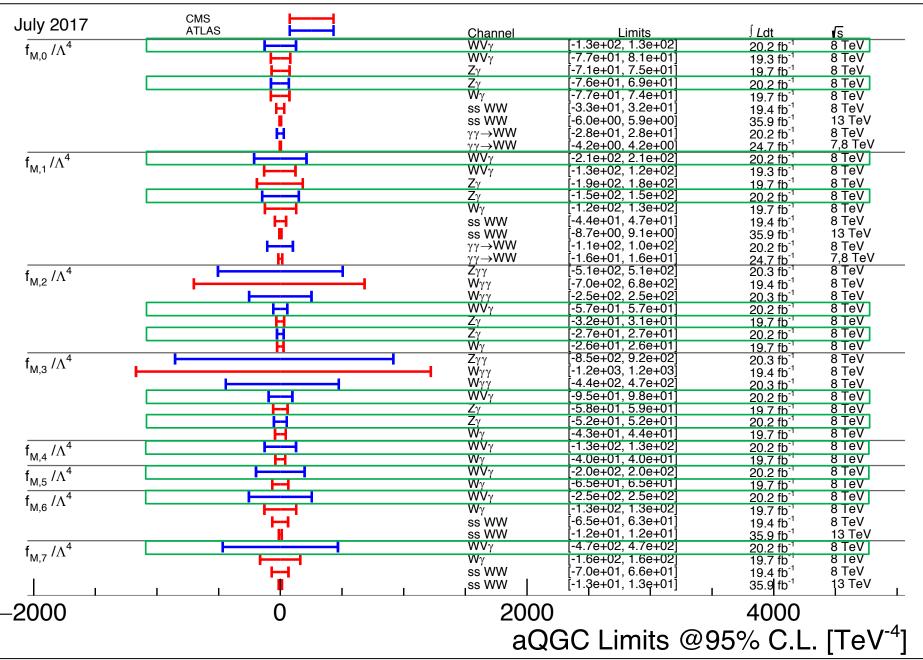
### aQGC constraints

• 18 dim-8 aQGC parameters are assessed with an effective theory (Eboli *et al.*, Phys.Rev. D 74, 073005 (2006))

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{j=0}^{1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0}^{7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j} + \sum_{j=0,1,2,5,6,7} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j}$$

3,4 and 6 vanished to respect gauge invariance

- $f_{S,j}$ : only cov. derivatives of Higgs field
- $f_{M,j}$ : only field strength tensors
- $f_{T,j}$ : field strength tensors and cov. derivatives of Higgs field



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC\_Results

# aQGC constraints with Z<sub>ijj</sub> analysis

#### • Madgraph formalism with $\Lambda_{\rm FF}$ = $\infty$

	Limits 95% CL	Measured $[TeV^{-4}]$	Expected $[\text{TeV}^{-4}]$
	$f_{T9}/\Lambda^4$	[-3.9, 3.9]	[-2.7, 2.8]
	$f_{T8}/\Lambda^4$	[-1.8, 1.8]	[-1.3, 1.3]
	$f_{T0}/\Lambda^4$	[-3.4, 2.9]	[-3.0, 2.3]
ATLAS $Z(\rightarrow \ell \bar{\ell} / \nu \bar{\nu}) \gamma$ -EWK	$f_{M0}/\Lambda^4$	[-76, 69]	[-66, 58]
	$f_{M1}/\Lambda^4$	[-147, 150]	[-123, 126]
	$f_{M2}/\Lambda^4$	[-27, 27]	[-23, 23]
	$f_{M3}/\Lambda^4$	[-52, 52]	[-43, 43]
	$f_{T9}/\Lambda^4$	[-4.0, 4.0]	[-6.0, 6.0]
	$f_{T8}/\Lambda^4$	[-1.8, 1.8]	[-2.7, 2.7]
CMS $Z(\to \ell \bar{\ell})\gamma$ -EWK	$f_{T0}/\Lambda^4$	[-3.8, 3.4]	[-5.1, 5.1]
	$f_{M0}/\Lambda^4$	[-71, 75]	[-109, 111]
	$f_{M1}/\Lambda^4$	[-190, 182]	[-281, 280]
	$f_{M2}/\Lambda^4$	[-32, 31]	[-47, 47]
	$f_{M3}/\Lambda^4$	[-58, 59]	[-87, 87]
	$f_{T0}/\Lambda^4$	[-5.4, 5.6]	[-3.2, 3.4]
	$f_{M0}/\Lambda^4$	[-77, 74]	[-47, 44]
CMS $W(\to \ell \nu)\gamma$ -EWK	$f_{M1}/\Lambda^4$	[-125, 129]	[-72, 79]
	$f_{M2}/\Lambda^4$	[-26, 26]	[-16, 15]
	$f_{M3}/\Lambda^4$	[-43, 44]	[-25, 27]

July 2017	CMS ATLAS	Channel	Limits	∫ <i>L</i> dt	ı/s
£ 1.4		Wyy	[-3.4e+01, 3.4e+01]	19.4 fb <sup>-1</sup>	8 TeV
$f_{T,0} / \Lambda^4$	· • • •	Wyy	[-1.6e+01, 1.6e+01]	20.3 fb <sup>-1</sup>	8 TeV
	· · · · · · · · · · · · · · · · · · ·	Ζγγ	[-1.6e+01, 1.9e+01]	20.3 fb <sup>-1</sup>	8 TeV
		WVy	[-1.8e+01, 1.8e+01]	20.2 fb <sup>-1</sup>	8 TeV
		WVγ	[-2.5e+01, 2.4e+01]	19.3 fb <sup>-1</sup>	8 TeV
	і ні	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb <sup>-1</sup>	8 TeV
	H	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb <sup>-1</sup>	8 TeV
	- H	Ŵγ	[-5.4e+00, 5.6e+00]	19.7 fb <sup>-1</sup>	8 TeV
	Ĥ	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb <sup>-1</sup>	8 TeV
	i i i	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb <sup>-1</sup>	13 TeV
		ZZ	[-4.6e-01, 4.4e-01]	35.9 fb <sup>-1</sup>	13 TeV
<b>f</b> / A 4		WVγ	[-3.6e+01, 3.6e+01]	20.2 fb <sup>-1</sup>	8 TeV
$f_{T,1} / \Lambda^4$	Н	Ζγ	[-4.4e+00, 4.4e+00]	19.7 fb <sup>-1</sup>	8 TeV
	Ĥ	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
	Ĥ	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb <sup>-1</sup>	8 TeV
	Ĩ	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb <sup>-1</sup>	13 TeV
		ZZ	[-6.1e-01, 6.1e-01]	35.9 fb <sup>-1</sup>	13 TeV
/ 4		WVγ	[-7.2e+01, 7.2e+01]	20.2 fb <sup>-1</sup>	8 TeV
f <sub>T,2</sub> /Λ <sup>4</sup>		Ζγ	[-9.9e+00, 9.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
	<u> </u>	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb <sup>-1</sup>	8 TeV
	<b>H</b>	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb <sup>-1</sup>	8 TeV
	H	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb <sup>-1</sup>	13 TeV
	Н	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb <sup>-1</sup>	13 TeV
- Τ,5 /Λ <sup>4</sup>	<b>⊢</b> −−−	Ζγγ	[-9.3e+00, 9.1e+00]	20.3 fb <sup>-1</sup>	8 TeV
T,5 //		WVγ	[-2.0e+01, 2.1e+01]	20.2 fb <sup>-1</sup>	8 TeV
	H	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb <sup>-1</sup>	8 TeV
<sub>Τ,6</sub> /Λ <sup>4</sup>		WVγ	[-2.5e+01, 2.5e+01]	20.2 fb <sup>-1</sup>	8 TeV
	H	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
$T_{,7}/\Lambda^4$		WVγ	[-5.8e+01, 5.8e+01]	20.2 fb <sup>-1</sup>	8 TeV
T,7 // X	<b>⊢_⊣</b>	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb <sup>-1</sup>	8 TeV
- Τ,8 /Λ <sup>4</sup>	Η	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb <sup>-1</sup>	8 TeV
T,8 // 1	Н	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb <sup>-1</sup>	8 TeV
	H	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb <sup>-1</sup>	13 TeV
114	<b>⊢</b> ⊣	Ζγγ	[-7.4e+00, 7.4e+00]	20.3 fb <sup>-1</sup>	8 TeV
$f_{T,9} / \Lambda^4$	н	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb <sup>-1</sup>	8 TeV
		Ζγ	[-3.9e+00, 3.9e+00]	20.2 fb <sup>-1</sup>	8 TeV
	H	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb <sup>-1</sup>	13 TeV
-100	0	100	200	)	30
		a	QGC Limits @	95% C.L	[TeV <sup>-4</sup> ]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC\_Results

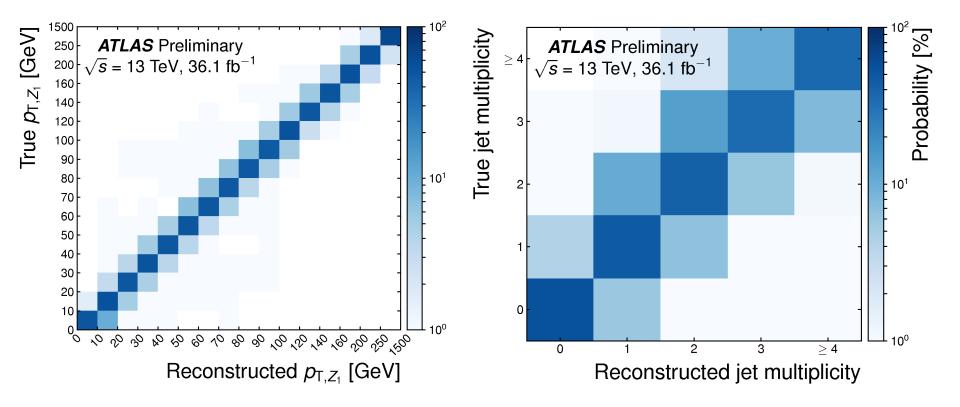
### Conclusions

- Showcased the full ATLAS multiboson programme
- Diboson productions:
  - 13 TeV analysis for ZZ,WZ and WW with full-leptonic modes
    - Accurate validations of SM at NNLO with  $\leq$ 10% precision
  - Adding sensitivity, in particular to aTGCs, with semileptonic modes
    - Developing new analysis technique (boosted jet reconstruction)
- Triboson productions and VBS:
  - ATLAS has more > 3.0  $\sigma$  evidence
    - SMVBS ssWW (<u>Phys. Rev. D 96, 012007</u>)
    - Exclusive  $\gamma\gamma \rightarrow WW$  (<u>Phys.Rev.D 94, 032011(2016)</u>
    - Triboson Wγγ (<u>Phys.Rev.Lett. 115 (2015) 3,031802</u>)
  - ATLAS measurements started setting stringent constraints on aQGCs
- No evidence for the BSM physics yet
  - Continue setting ever more stringent constraints on aTGCs/ aQGCs

### Back up

• Rij are defined as the probability of an event in true bin j being observed with the detector in bin i

$$m_i = R_{ij}t_j.$$



#### <u>arXiv: 1702.04519</u>

30

# WW full-leptonic @ I3 TeV

$pp \rightarrow WW$ sub-process	Order of	$\sigma_{WW}^{ m tot}$	A	$\sigma^{\rm fid}_{WW \to e\mu}$
	$lpha_{ m s}$	[pb]	[%]	[fb] '
$q\bar{q}$ [9,13]	${\cal O}(lpha_{ m s}^2)$	$111.1 \pm 2.8$	$16.20 \pm 0.13$	$422 \ \ + \ \ 12 \ \ - \ \ 11$
gg (non-resonant) [33]	${\cal O}(lpha_{ m s}^3)$	$6.82 \substack{+ & 0.42 \\ - & 0.55 }$	$28.1 \ + \ 2.7 \ - \ 2.3$	$44.9 \pm 7.2$
$gg \to H \to WW$ [67][30]	$\mathcal{O}(\alpha_{\rm s}^5)$ tot. / $\mathcal{O}(\alpha_{\rm s}^3)$ fid.	$10.45 \substack{+ & 0.61 \\ - & 0.79 \end{bmatrix}$	$4.5 \pm 0.6$	$11.0 \pm 2.1$
$q\bar{q} + gg \text{ (non-resonant)} + gg \rightarrow H \rightarrow WW$	nNNLO+H	$128.4 \ \ + \ \ 3.5 \ \ - \ \ 3.8$	$15.87^{+0.17}_{-0.14}$	$478 \pm 17$