

# Vector Boson Scattering, Triple Gauge-Boson Final States, and Limits on Anomalous Quartic Gauge Couplings with the ATLAS Detector

Christian (Alex) Johnson  
on behalf of the ATLAS Collaboration

Indiana University

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25<sup>th</sup> Deep Inelastic Scattering



# Outline

Physics Motivation

VBS Final States

Exclusive  $\gamma\gamma \rightarrow W^+W^-$   
 $W^\pm W^\pm jj$   
 $Z\gamma jj$

Tri-boson Final States

$W^\pm W^\pm W^\mp$

Summary

- ▶ Vector Boson Scattering (VBS) and Tri-boson processes provide a unique way to probe the mechanism of electroweak symmetry breaking (EWSB)
- ▶ Cross section measurements can be used to test whether the Higgs discovered at the LHC fully unitarizes the VBS scattering amplitudes
- ▶ Gauge boson self-couplings are fixed in the SM
  - ▶ only charged QGCs are allowed ( $WWWW$ ,  $WWZZ$ ,  $WWZ\gamma$ ,  $WW\gamma\gamma$ )
  - ▶ probe new physics through deviations from SM
  - ▶ constrain anomalous quartic gauge couplings (aQGCs) independent of model

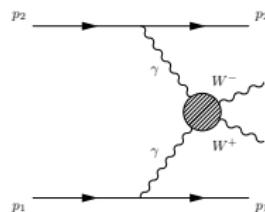
All measurements and limits in this presentation are extracted from the entire  $20.3 \text{ fb}^{-1}$   $\sqrt{s} = 8 \text{ TeV}$  dataset.

- ▶ An effective field theory (EFT) with higher-dimensional operators is adopted to parameterize the anomalous couplings.

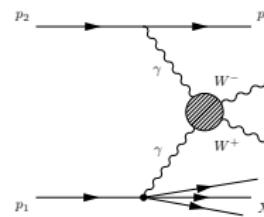
- ▶ A parity-conserving EFT Lagrangian is constructed based on a Higgs boson that belongs to an  $SU(2)_L$  doublet.

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_+ + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j$$

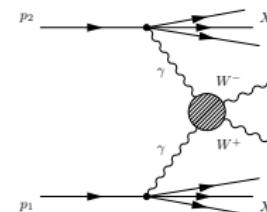
- ▶ The dimension-8 operator coefficients ( $f_j$ ), are sub-categorized into longitudinal-only ( $f_{S,x}$ ), transverse-only ( $f_{T,x}$ ), and mixed longitudinal/transverse parameters ( $f_{M,x}$ ).
  - ▶ Formalism used by VBFNLO and MadGraph5

Exclusive  $\gamma\gamma \rightarrow W^+W^-$ Exclusive  $\gamma\gamma \rightarrow W^+W^-$ : [arXiv:1607.03745]

(a) Elastic production



(b) Single-dissociation



(c) Double-dissociation

Exclusive  $\gamma\gamma \rightarrow W^+W^-$ 

## Selection

- ▶ These events are produced when each proton emits a photon and the two annihilate, either via  $t$ - and  $u$ -channel  $W$ -exchange involving trilinear gauge-boson couplings or via the  $WW\gamma\gamma$  QGC to create a  $W^+W^-$  pair.
- ▶ Exclusive candidates are characterized by an absence of tracks other than those from the  $W^+W^-$  pair decay products
  - ▶ In all three cases, protons never enter the acceptance of the ATLAS detector.

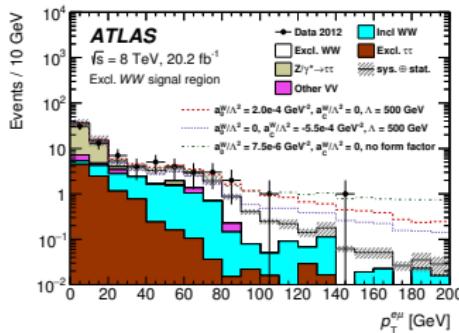
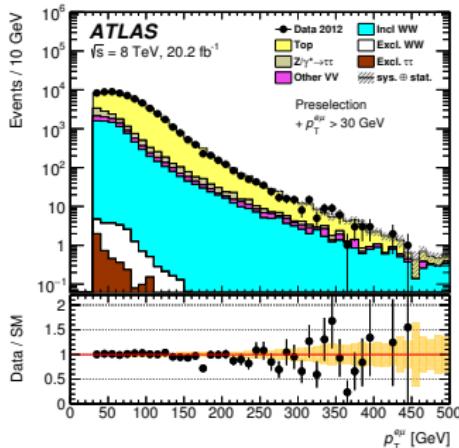
	$W^+W^-$ selection	Higgs boson selection
Oppositely charged $e\mu$ final states		
<i>Preselection</i>	$p_T^{\ell 1} > 25 \text{ GeV}$ and $p_T^{\ell 2} > 20 \text{ GeV}$	$p_T^{\ell 1} > 25 \text{ GeV}$ and $p_T^{\ell 2} > 15 \text{ GeV}$
	$m_{e\mu} > 20 \text{ GeV}$	$m_{e\mu} > 10 \text{ GeV}$
$p_T^{e\mu} > 30 \text{ GeV}$		
Exclusivity selection, $\Delta z_0^{\text{iso}}$		
aQGC signal	$p_T^{e\mu} > 120 \text{ GeV}$	—
Spin-0 Higgs boson	—	$m_{e\mu} < 55 \text{ GeV}$ $\Delta\phi_{e\mu} < 1.8$ $m_T < 140 \text{ GeV}$

Exclusivity requires zero additional tracks with  $p_T > 0.4 \text{ GeV}$  near  $z_0^{\text{av}}$  such that  $|z_0^{\text{track}} - z_0^{\text{av}}| < \Delta z_0^{\text{iso}}$  and  $z_0^{\text{av}}$  is the average  $z_0$  of the tagged leptons.  $\Delta z_0^{\text{iso}} = 1 \text{ mm}$ .

Exclusive  $\gamma\gamma \rightarrow W^+W^-$ 

## Measurements

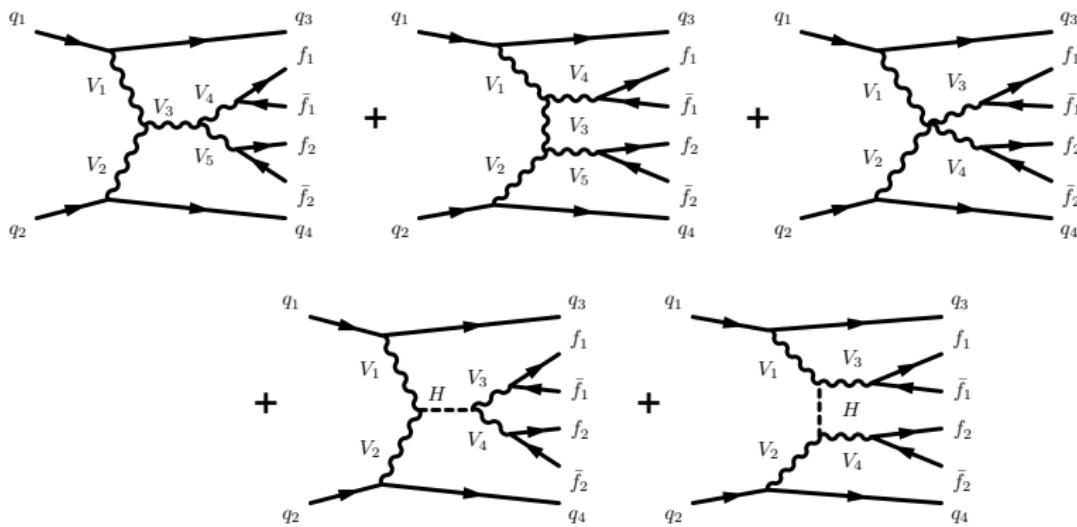
- ▶ Good agreement (within 0.5%) between data and background prediction is observed before exclusivity selection
  - ▶ Largest backgrounds: non-resonant  $q\bar{q} \rightarrow W^+W^-$ ,  $gg \rightarrow W^+W^-$ , and resonant  $H \rightarrow W^+W^-$
- ▶ After exclusivity cut, overall event yield agrees to within 2% in the  $e\mu$  final state
- ▶  $\sigma_{\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp X}^{Measured} = 6.9 \pm 2.2 \text{ (stat.)} \pm 1.4 \text{ (syst.) fb}$  with a significance of  $3.0\sigma$



## aQGCs

- ▶ Particularly sensitive to the  $WW\gamma\gamma$  coupling
- ▶ Was performed using the region  $p_T^{e\mu} > 120$  GeV. Where aQGC contributions are expected to be important and SM backgrounds are suppressed.
- ▶ The 95% CL limits on the couplings  $f_{M,0}/\Lambda^4$  and  $f_{M,1}/\Lambda^4$  are extracted with a likelihood test using the one observed data event as a constraint. Couplings use a dipole form factor to preserve unitarity at high  $m_{\gamma\gamma}$ .

Coupling	$\Lambda_{\text{cutoff}}$	Observed allowed range [ $GeV^{-4}$ ]	Expected allowed range [ $GeV^{-4}$ ]
$f_{M,0}/\Lambda^4$	500 GeV	$[-3.7 \times 10^{-9}, 3.6 \times 10^{-9}]$	$[-3.5 \times 10^{-9}, 3.4 \times 10^{-9}]$
$f_{M,1}/\Lambda^4$	500 GeV	$[-13 \times 10^{-9}, 14 \times 10^{-9}]$	$[-12 \times 10^{-9}, 13 \times 10^{-9}]$
$f_{M,0}/\Lambda^4$	$\infty$	$[-6.6 \times 10^{-11}, 6.6 \times 10^{-11}]$	$[-5.8 \times 10^{-11}, 6.2 \times 10^{-11}]$
$f_{M,1}/\Lambda^4$	$\infty$	$[-24 \times 10^{-11}, 25 \times 10^{-11}]$	$[-23 \times 10^{-11}, 23 \times 10^{-11}]$

$w^\pm w^\pm jj$  $W^\pm W^\pm jj$ : [arXiv:1611.02428]

# Selection

- ▶ For  $VVjj$  final states, the  $W^\pm W^\pm jj$  channel has the largest cross-section ratio of EWK and QCD production
- ▶ The presence of two same-sign leptons significantly reduces the SM backgrounds

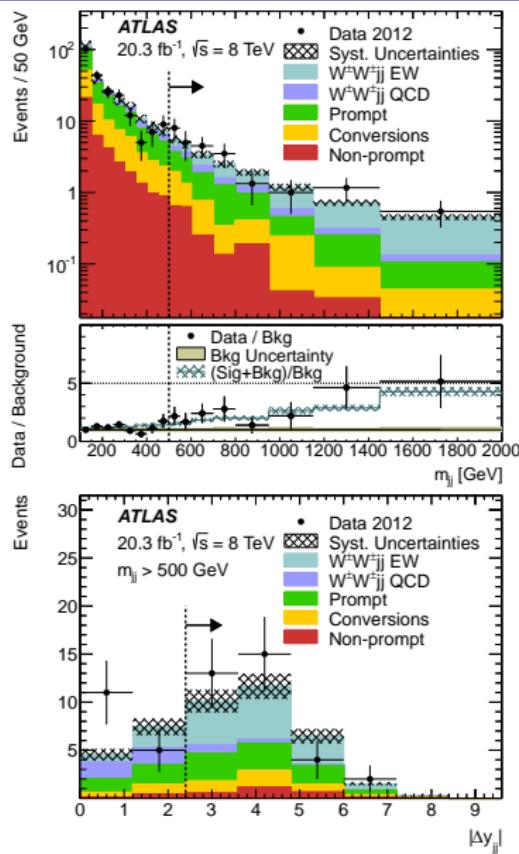
Signal Region		Selection Criteria
Inclusive	Lepton	Exactly two tight same-electric-charge leptons with $p_T > 25$ GeV
	Jet	At least two jets with $p_T > 30$ GeV and $ \eta  < 4.5$
	$m_{\ell\ell}$	$m_{\ell\ell} > 20$ GeV
	$E_T^{\text{miss}}$	$E_T^{\text{miss}} > 40$ GeV
	$Z$ veto	$ m_{\ell\ell} - m_Z  > 10$ GeV (only for the $e^\pm e^\pm$ channel)
	Third-lepton veto	No third veto-lepton
	$b$ -jet veto	No identified $b$ -jets with $p_T > 30$ GeV and $ \eta  < 2.5$
	$m_{jj}$	$m_{jj} > 500$ GeV
VBS	$\Delta y_{jj}$	$ \Delta y_{jj}  > 2.4$
aQGC	$m_{WW,\text{T}}$	$m_{WW,\text{T}} > 400$ GeV

- ▶ Inclusive: EWK, QCD, and interference are treated as signal
- ▶ VBS: EWK and interference are treated as signal

$w^\pm w^\pm jj$ 

## Measurements

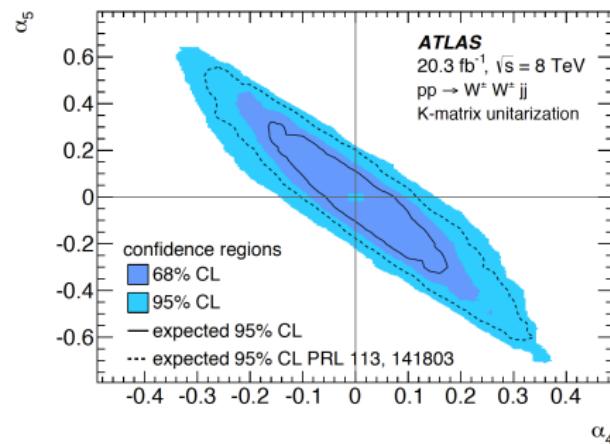
- ▶ Discrimination improves when  $M_{jj} > 500$  GeV
- ▶  $\sigma_{W^\pm W^\pm jj}^{Incl.} = 2.3 \pm 0.6$  (stat.)  $\pm 0.3$  (syst.) fb with a significance of  $4.5\sigma$
- ▶ We see the EWK events have larger  $|\Delta y_{jj}|$  than QCD
- ▶  $\sigma_{W^\pm W^\pm jj}^{VBS} = 1.5 \pm 0.5$  (stat.)  $\pm 0.2$  (syst.) fb with a significance of  $3.6\sigma$



$w^\pm w^\pm jj$ 

## aQGCs

- ▶ WHIZARD is used to simulate  $W^\pm W^\pm jj$  with aQGCs
  - ▶ Uses a different formalism than VBFNLO
  - ▶ Vary  $\alpha_4$  and  $\alpha_5$  which are related to  $f_S$
- ▶ We find a 35% improvement in the expected aQGC sensitivity with respect to previous ATLAS ssWW analysis



Observed:

$$-0.14 < \alpha_4 < 0.15$$

$$-0.22 < \alpha_5 < 0.22$$

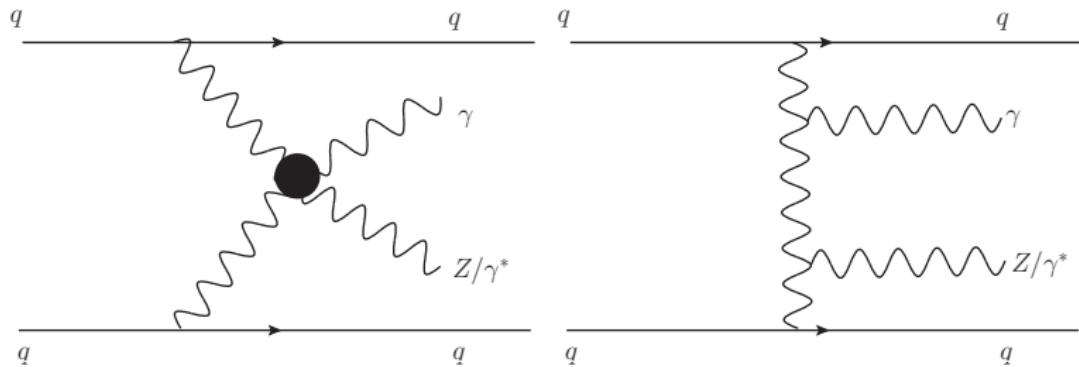
Expected:

$$-0.06 < \alpha_4 < 0.07$$

$$-0.10 < \alpha_5 < 0.11$$

$Z\gamma jj$ 

# $Z\gamma jj$ : [CERN-EP-2017-046]



# Selection

- ▶ EWK-enriched search region is characterized by two energetic, hadronic jets with wide rapidity separation and large dijet invariant mass.
- ▶ While the vector-boson pair is produced more centrally

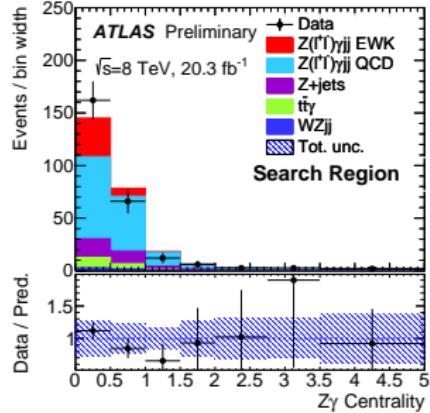
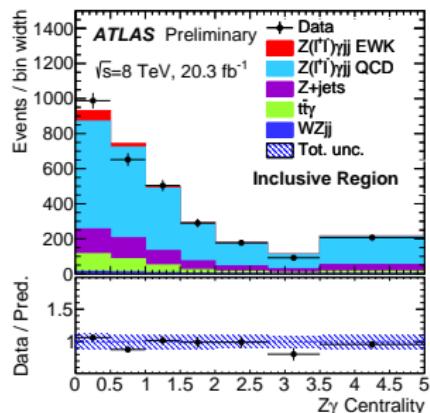
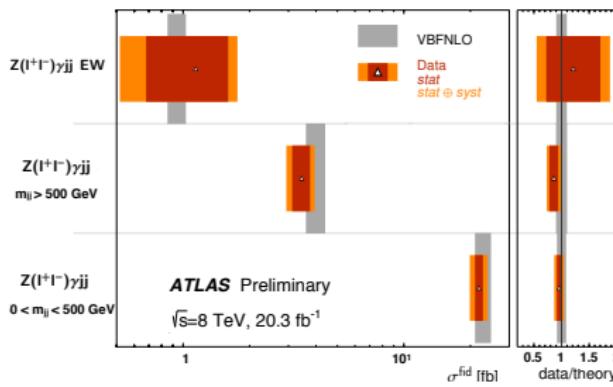
Objects	Particle- (Parton-) level selection
Leptons	$p_T^\ell > 25 \text{ GeV}$ and $ \eta^\ell  < 2.5$ Dressed leptons, OS charge
Photon (kinematics)	$p_T^\gamma > 15 \text{ GeV}$ , $ \eta^\gamma  < 2.37$ $\Delta R(\ell, \gamma) > 0.4$
Photon (isolation)	$E_T^{\text{iso}} < 0.5 \cdot E_T^\gamma$ (no isolation)
FSR cut	$m_{\ell\ell} + m_{\ell\gamma\gamma} > 182 \text{ GeV}$ $m_{\ell\ell} > 40 \text{ GeV}$
Particle jets (Outgoing partons) ( $j = \text{jets}$ ) ( $p = \text{outgoing quarks or gluons}$ )	At least two jets (outgoing partons) $E_T^{j(p)} > 30 \text{ GeV}$ , $ \eta^{j(p)}  < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$
Control region (CR)	$150 < m_{jj(pp)} < 500 \text{ GeV}$
Search region (SR)	$m_{jj(pp)} > 500 \text{ GeV}$
aQGC region	$m_{jj(pp)} > 500 \text{ GeV}$ $E_T^\gamma > 250 \text{ GeV}$

Blue box defines the Inclusive region. The search, control, and aQGC regions have an added  $M_{jj}$  requirement

$Z\gamma jj$ 

## Measurements

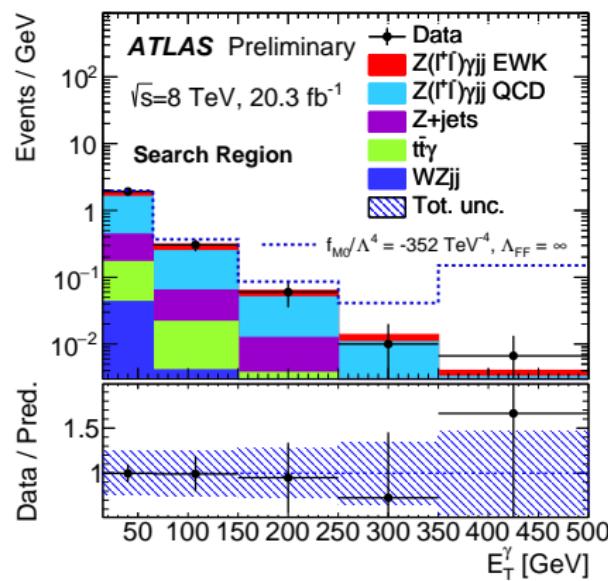
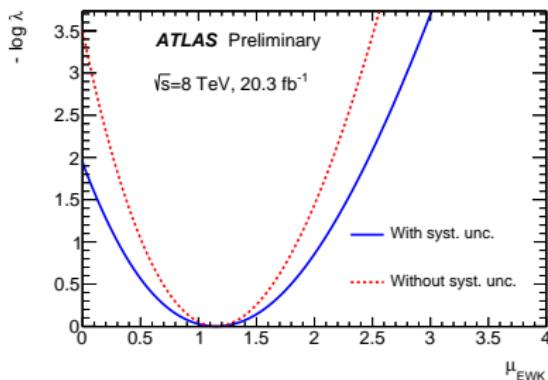
- ▶ A fit to a centrality observable,  $\zeta$ , is used to extract the cross-section.
- ▶  $\zeta_{Z\gamma} \equiv \left| \frac{\eta_{Z\gamma} - \frac{\eta_{j1} + \eta_{j2}}{2}}{\eta_{j1} - \eta_{j2}} \right|$



# aQGCs

Optimization studies show that selection of events with  $E_T^{\gamma} > 150(250)$  GeV for the neutrino (charged-lepton) channels maximizes the sensitivity to aQGC for the available amount of data.

- ▶ Then a log-likelihood method is used to extract the cross-sections from data.



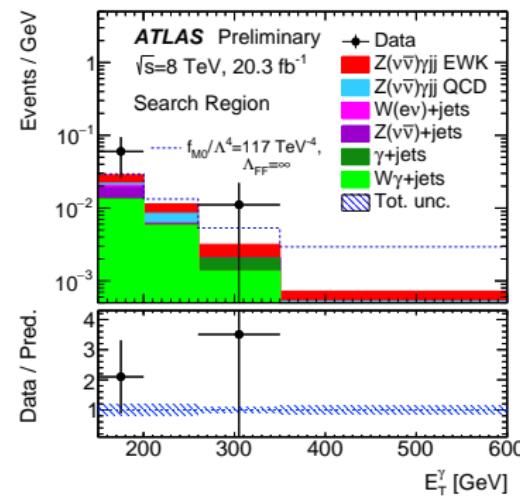
$Z\gamma jj$ 

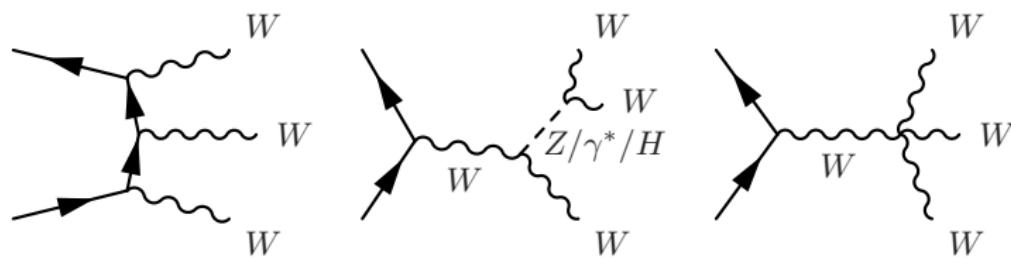
## aQGCs

Operators probed:

$f_{T0}/\Lambda^4$  as a representative of  $f_{T1}/\Lambda^4$  and  $f_{T2}/\Lambda^4$ ;  
 $f_{T8}/\Lambda^4$  and  $f_{T9}/\Lambda^4$ ;  
 $f_{M0}/\Lambda^4$ ,  $f_{M1}/\Lambda^4$ ,  $f_{M2}/\Lambda^4$ , and  $f_{M3}/\Lambda^4$

- ▶ The neutrino channel provides best expected limits for all operators, but combining the channels improved results by 5-10%.
- ▶ These limits are competitive with previous constraints obtained with events with  $Z\gamma jj$  and different final states



$w^\pm w^\pm w^\mp$  $W^\pm W^\pm W^\mp$ : [arXiv:1610.05088]

$w^\pm w^\pm w^\mp$ 

# Selection

- ▶ Two decays channels:  $\ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$ ,  $\ell^\pm \nu \ell^\pm \nu jj$  with  $\ell = e, \mu$
- ▶ For  $\ell \nu \ell \nu \ell \nu$  candidates, there are eight different final states based on the flavor and charge of the leptons. (Same-Flavor Opposite-Sign)

$\ell \nu \ell \nu \ell \nu$	0 SFOS	1 SFOS	2 SFOS
Preselection	Exactly three charged leptons with $p_T > 20$ GeV		
$E_T^{\text{miss}}$	-	$E_T^{\text{miss}} > 45$ GeV	$E_T^{\text{miss}} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV		
Angle between trilepton and $\vec{p}_T^{\text{miss}}$	$ \phi^{3\ell} - \phi^{\vec{p}_T^{\text{miss}}}  > 2.5$		
Z boson veto	$ m_{ee} - m_Z  > 15$ GeV	$m_Z - m_{\text{SFOS}} > 35$ GeV or $m_{\text{SFOS}} - m_Z > 20$ GeV	$ m_{\text{SFOS}} - m_Z  > 20$ GeV
Jet veto	At most one jet with $p_T > 25$ GeV and $ \eta  < 4.5$		
b-jet veto	No identified b-jets with $p_T > 25$ GeV and $ \eta  < 2.5$		

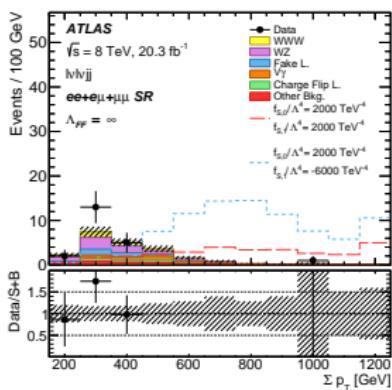
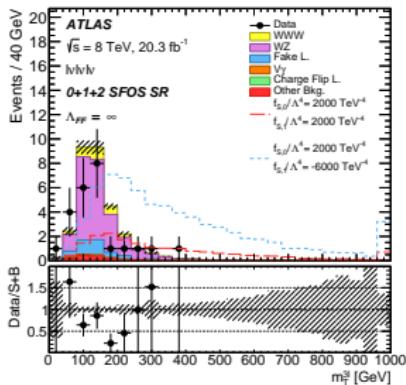
$\ell \nu \ell \nu jj$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Lepton	Exactly two same-charge leptons with $p_T > 30$ GeV		
Jets	At least two jets with $p_T(1) > 30$ GeV, $p_T(2) > 20$ GeV and $ \eta  < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
$E_T^{\text{miss}}$	$E_T^{\text{miss}} > 55$ GeV	-	-
$m_{jj}$	$65$ GeV $< m_{jj} < 105$ GeV		
$\Delta\eta_{jj}$	$ \Delta\eta_{jj}  < 1.5$		
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV	-	-
Third-lepton veto	No third lepton with $p_T > 6$ GeV and $ \eta  < 2.5$ passing looser identification requirements		
b-jet veto	No identified b-jets with $p_T > 25$ GeV and $ \eta  < 2.5$		

$w^\pm w^\pm w^\mp$ 

## Measurements

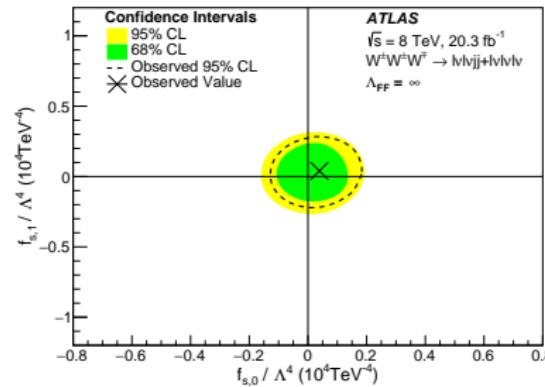
- ▶ Data are found to be in good agreement with the SM predictions in all signal regions.
- ▶ The combined observed (expected) significance of a positive, signal cross section is  $0.96\sigma$  ( $1.05\sigma$ ).
- ▶ The observed (expected) upper limit on the fiducial cross section: 1.3 fb (1.1 fb) in the  $\ell\nu\ell\nu\ell\nu$  channel and 1.1 fb (0.9 fb) in  $\ell\nu\ell\nu jj$  channel.

	Cross section [fb]	
	Theory	Observed
Fiducial		
$\ell\nu\ell\nu\ell\nu$	$0.309 \pm 0.007$ (stat.) $\pm 0.015$ (PDF) $\pm 0.008$ (scale)	$0.31^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
$\ell\nu\ell\nu jj$	$0.286 \pm 0.006$ (stat.) $\pm 0.015$ (PDF) $\pm 0.010$ (scale)	$0.24^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (syst.)
Total	$241.5 \pm 0.1$ (stat.) $\pm 10.3$ (PDF) $\pm 6.3$ (scale)	$230 \pm 200$ (stat.) $^{+150}_{-160}$ (syst.)



## aQGCs

- ▶ This process is particularly sensitive to the  $WWWW$  coupling
- ▶ Studies were performed using a grid of LO VBFNLO events with different values of  $f_{S,0}/\Lambda^4$  and  $f_{S,1}/\Lambda^4$
- ▶ These events are scaled to NLO using the ratio of SM LO to NLO predictions.
- ▶ Profile-likelihood scans are performed on the combinations of all six SRs.



## Summary

- ▶ Presented four analyses whose final states are favorable for probing aQGCs
- ▶ Together these analyses test 9 different dimension-8 operators found in EFT.
- ▶ We have placed competitive limits on these operators using the entire 8 TeV dataset.
- ▶ Evidence of exclusive  $\gamma\gamma \rightarrow W^+W^-$  production
- ▶ Evidence of EWK  $W^\pm W^\pm jj$  production
- ▶ First search for  $WWWW$  QGC interactions via triboson  $W^\pm W^\pm W^\mp$  production

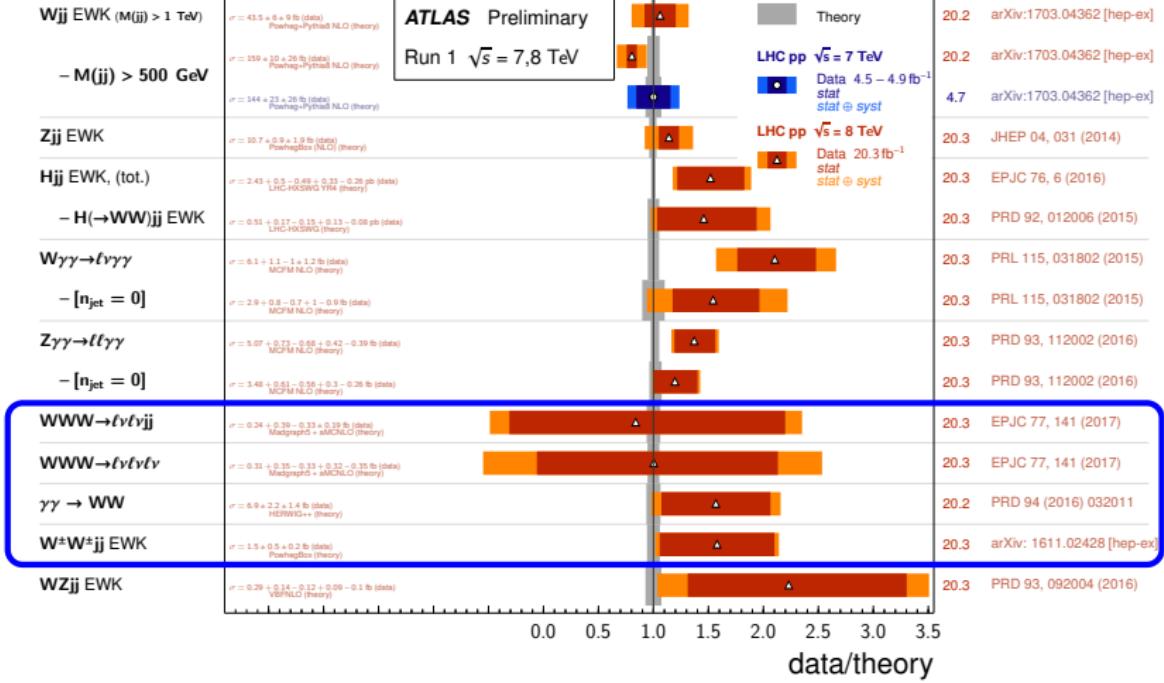
# BACKUP

## VBF, VBS, and Triboson Cross Section Measurements

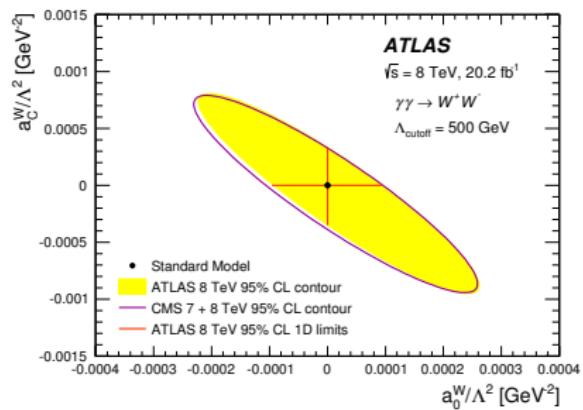
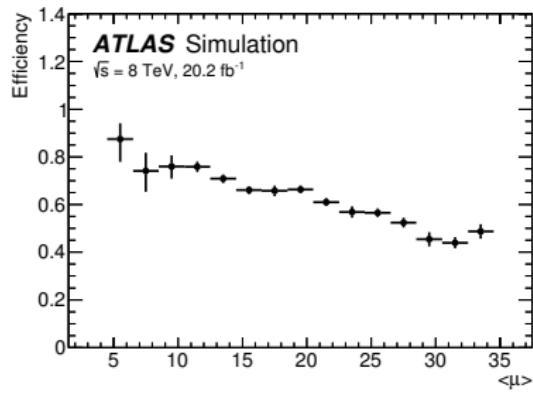
Status: March 2017

$\int \mathcal{L} dt$   
( $\text{fb}^{-1}$ )

Reference



# Exclusive $\gamma\gamma \rightarrow W^+W^-$



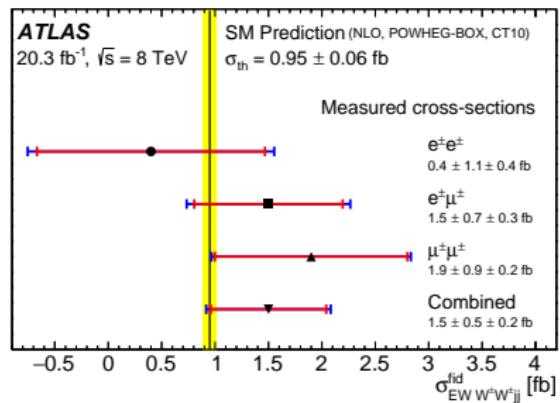
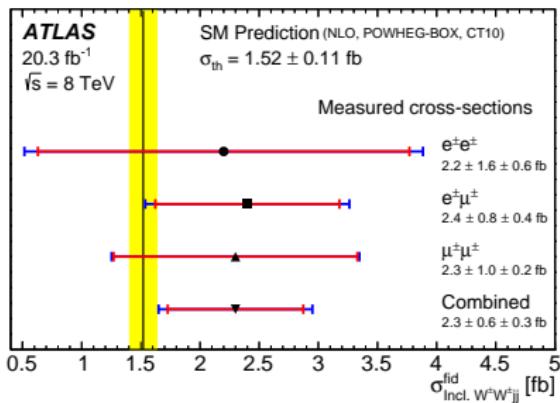
# Exclusive $\gamma\gamma \rightarrow W^+W^-$

Source of uncertainty	Uncertainty [%]
Statistics	33%
Background determination	18%
Exclusivity signal efficiency	10%
All other	< 5%
Total	39%

	Expected Signal	Data	Total Bkg	Incl $W^+W^-$	Excl. $\tau\tau$	Other- $VV$	Other Bkg	SM/Data	$\epsilon A$ (Signal)
Preselection	$22.6 \pm 1.9$	99424	97877	11443	21.4	1385	85029	0.98	0.254
$p_T^{jet} > 30$ GeV	$17.6 \pm 1.5$	63329	63023	8072	4.30	896.3	54051	1.00	0.198
$\Delta_{\gamma\gamma}^{\text{iso}}$ requirement	$9.3 \pm 1.2$	23	$8.3 \pm 2.6$	$6.6 \pm 2.5$	$1.4 \pm 0.3$	$0.3 \pm 0.2$	—	0.77	$0.105 \pm 0.012$
aQGC signal region									
$p_T^{jet} > 120$ GeV	$0.37 \pm 0.04$	1	$0.37 \pm 0.13$	$0.32 \pm 0.12$	$0.05 \pm 0.03$	0	—	0.74	$0.0042 \pm 0.0005$

Coupling	$\Lambda_{\text{cutoff}}$	Observed allowed range [ $GeV^{-4}$ ]	Expected allowed range [ $GeV^{-4}$ ]
$f_{M,0}/\Lambda^4$	500 GeV	$[-3.7 \times 10^{-9}, 3.6 \times 10^{-9}]$	$[-3.5 \times 10^{-9}, 3.4 \times 10^{-9}]$
$f_{M,1}/\Lambda^4$	500 GeV	$[-13 \times 10^{-9}, 14 \times 10^{-9}]$	$[-12 \times 10^{-9}, 13 \times 10^{-9}]$
$f_{M,0}/\Lambda^4$	$\infty$	$[-6.6 \times 10^{-11}, 6.6 \times 10^{-11}]$	$[-5.8 \times 10^{-11}, 6.2 \times 10^{-11}]$
$f_{M,1}/\Lambda^4$	$\infty$	$[-24 \times 10^{-11}, 25 \times 10^{-11}]$	$[-23 \times 10^{-11}, 23 \times 10^{-11}]$

# $W^\pm W^\pm jj$



# $W^\pm W^\pm jj$

Observed [TeV $^{-4}$ ]:

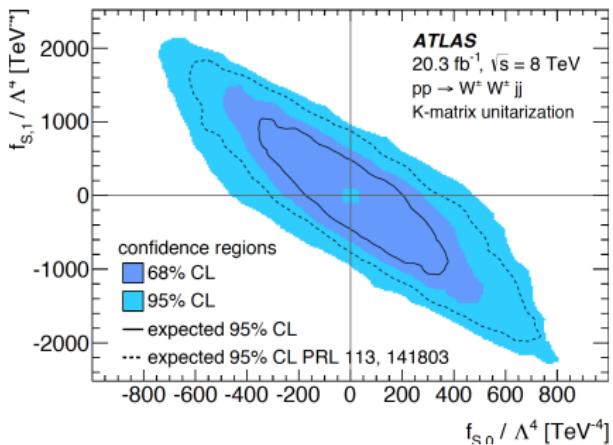
$$-459 < f_{S,0}/\Lambda^4 < 480$$

$$-961 < f_{S,1}/\Lambda^4 < 962$$

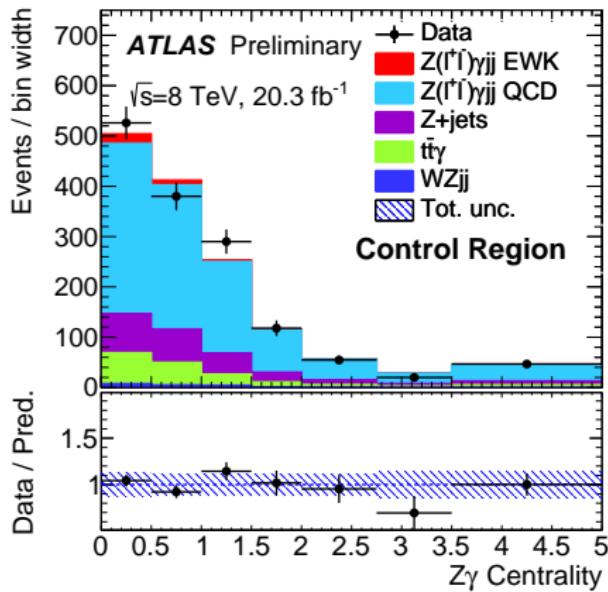
Expected [TeV $^{-4}$ ]:

$$-173 < f_{S,0}/\Lambda^4 < 205$$

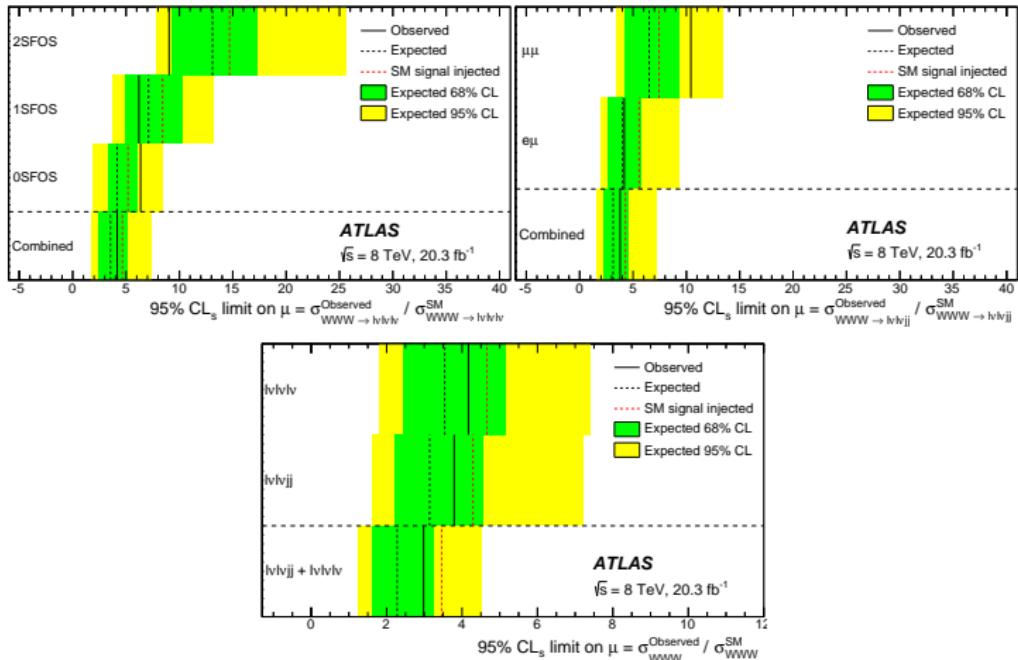
$$-458 < f_{S,1}/\Lambda^4 < 485$$



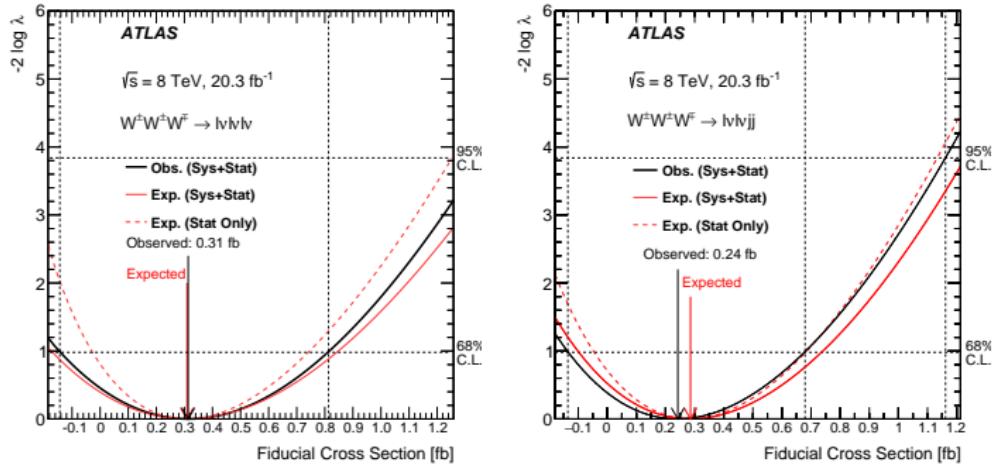
$Z\gamma jj$



$W^\pm W^\pm W^\mp$



# $W^\pm W^\pm W^\mp$



$\Lambda_{FF}$ [TeV]	Expected CI [ $\times 10^4 \text{ TeV}^{-4}$ ]		Observed CI [ $\times 10^4 \text{ TeV}^{-4}$ ]	
	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$	$f_{S,0}/\Lambda^4$	$f_{S,1}/\Lambda^4$
0.5	[-0.79, 0.89]	[-1.06, 1.27]	[-0.74, 0.86]	[-0.99, 1.20]
1	[-0.36, 0.41]	[-0.52, 0.60]	[-0.34, 0.40]	[-0.48, 0.58]
2	[-0.22, 0.25]	[-0.33, 0.39]	[-0.20, 0.24]	[-0.29, 0.36]
3	[-0.19, 0.22]	[-0.29, 0.36]	[-0.16, 0.21]	[-0.25, 0.33]
$\infty$	[-0.16, 0.19]	[-0.25, 0.30]	[-0.13, 0.18]	[-0.21, 0.27]