



# Recent Results on VBS, Exclusive WW and Tri-boson Production from ATLAS

QCD@LHC 2016

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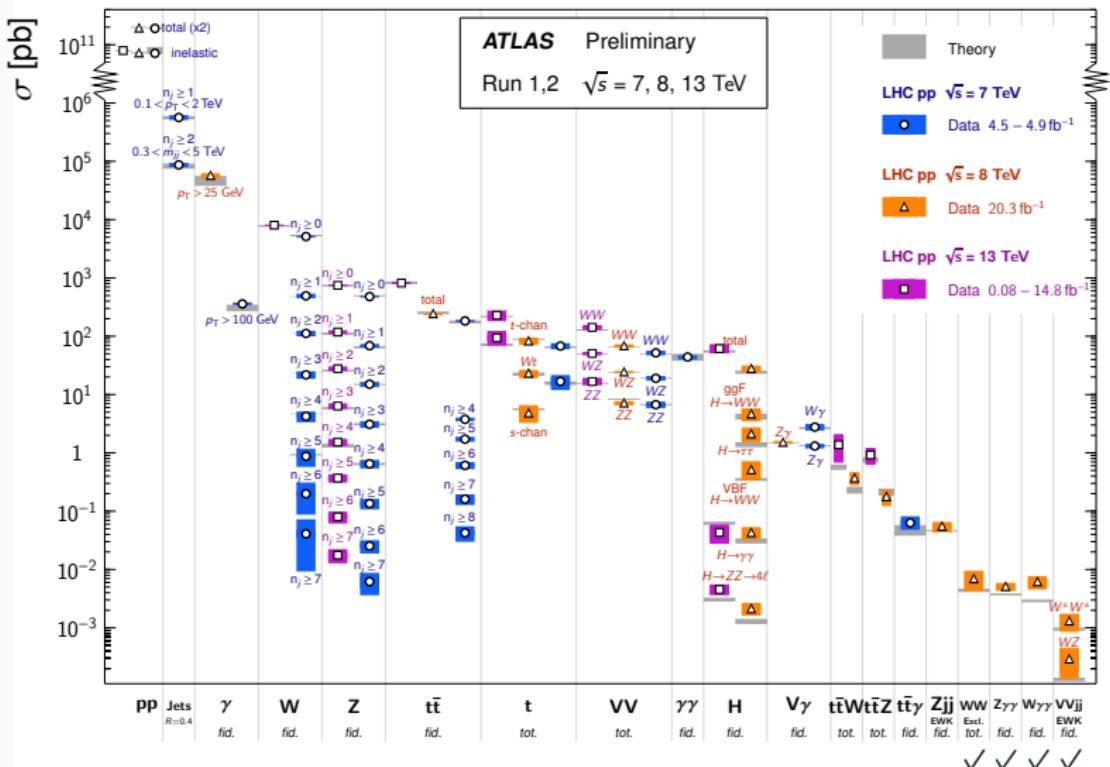
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On behalf of the ATLAS Collaboration

# SM Cross Section Measurement

## Standard Model Production Cross Section Measurements

Status: August 2016



# Anomalous Gauge Couplings

Electroweak theory is non-Abelian.

- Gauge bosons should interact among themselves. .

Effect of new physics at low energy scale can be parametrized by an effective Lagrangian..

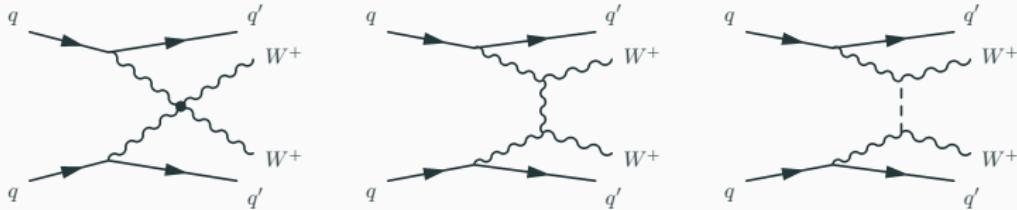
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \sum_{\text{dimension } d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

Dimension 4	Dimension 6	Dimension 8
WWWW, WWZZ non-linear representation $\alpha_4, \alpha_5$	WWZ $\gamma$ , WW $\gamma\gamma$ non-linear representation $\alpha_0/\lambda^2, \alpha_c/\lambda^2$	all VVVV linear representation $f_{S,i}/\lambda^4, f_{M,i}/\lambda^4, f_{T,i}/\lambda^4$

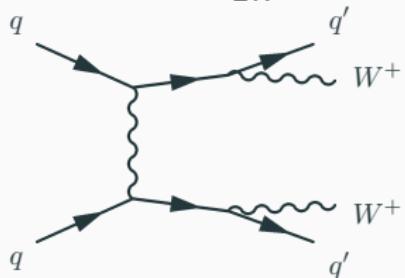
Effective Field Theory description: [arXiv:hep-ph/0606118](https://arxiv.org/abs/hep-ph/0606118)

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

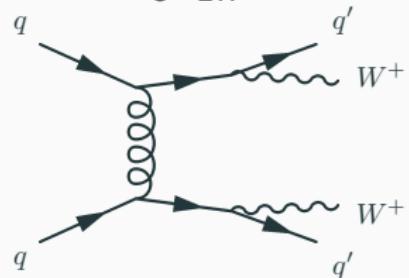
- $\sqrt{s} = 8 \text{ TeV}, \int L = 20.3 \text{ fb}^{-1}$ , [arXiv:1405.6241](#)
- Electroweak ( $\alpha_{EW}^4$  at LO) VBS:



- Electroweak ( $\alpha_{EW}^4$  at LO) non-VBS:



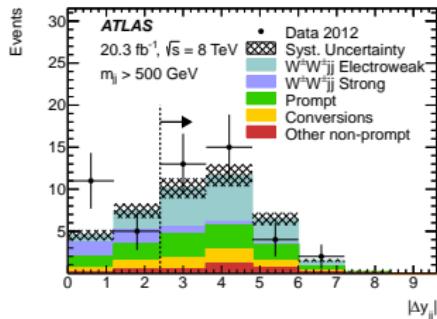
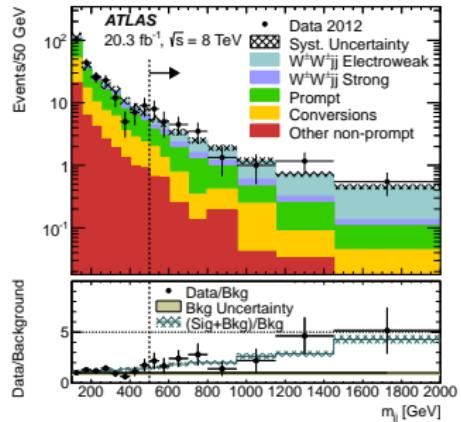
- Strong ( $\alpha_S^2 \alpha_{EW}^2$  at LO):



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

- First search for  $W^\pm W^\pm jj$  production.
- Sensitive to new physics via aQGC.
- For EW+Strong measurement(Inclusive region):
  - Two same charge leptons with  $p_T > 25$  GeV and  $|\eta| < 2.5$ .
  - At least 2 jets with  $p_T > 30$  GeV and  $|\eta| < 4.5$ ,  $\Delta R_{lj} > 0.3$ .
  - $m_{ll} > 20$  GeV,  $\Delta R_{ll} > 0.3$ ,  $E_T^{miss} > 40$  GeV,  $m_{jj} > 500$  GeV.
- For EW only measurement(VBS region)
  - Additional cut  $\Delta|y_{jj}| > 2.4$ .
- Backgrounds:
  - Prompt background like  $WZ/\gamma^*(MC)$ .
  - Conversion background like  $W\gamma(MC)$ .
  - Non-prompt background like  $W+jets$ ,  $t\bar{t}$ (Data-driven).

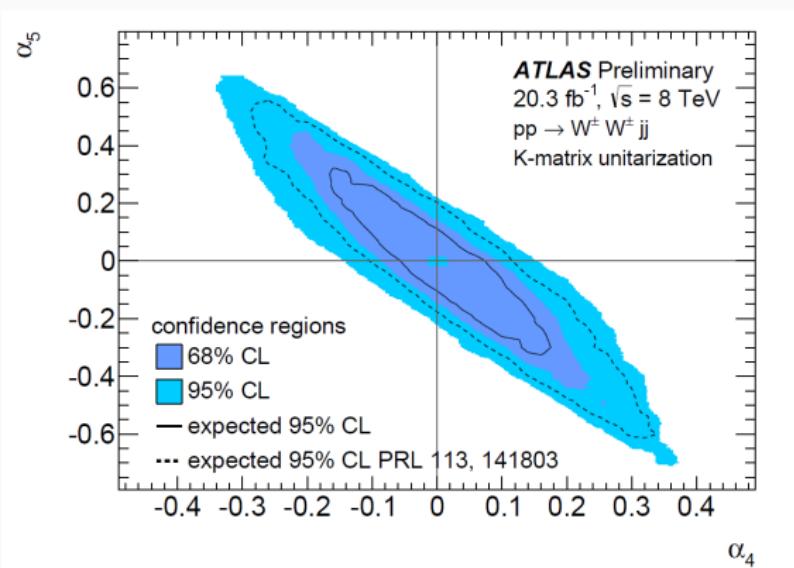
# $W^\pm W^\pm jj$ Cross Section



- Measured and predicted cross section of inclusive production:  
 $\sigma_{measured}^{fid} = 2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst}) \text{ fb}$ ,  $\sigma_{predicted}^{fid} = 1.52 \pm 0.11 \text{ fb}$ .
- Measured and predicted cross section of EW production(including interference with strong production):  
 $\sigma_{measured}^{fid} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst}) \text{ fb}$ ,  $\sigma_{predicted}^{fid} = 0.95 \pm 0.06 \text{ fb}$ .

# $W^\pm W^\pm \text{jj aQGCs}$

- Measurement in VBS region is used to study the aQGCs from  $WWWW$  vertex.
- The  $M_T > 400$  GeV cut is applied to improve the limits on aQGCs by 35% comparing to old result(the PRL).



# $W^\pm Z$ Production

$\sqrt{s} = 8 \text{ TeV}$ ,  $\int L = 20.3 \text{ fb}^{-1}$ , [arXiv:1607.03745](https://arxiv.org/abs/1607.03745)

VBS phase space

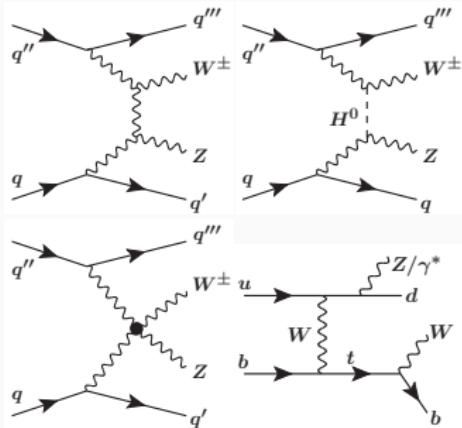
- Lepton  $|\eta| < 2.5$ ,  $p_T$  of  $l_Z > 15 \text{ GeV}$  and  $p_T$  of  $l_W > 20$ ,  $|m_Z - m_Z^{PDG}| < 10 \text{ GeV}$ ,  $m_T^W > 30 \text{ GeV}$ ,  $p_T$  of two leading jets  $> 30 \text{ GeV}$ ,  $|\eta|$  of two leading jets  $< 4.5$ , at least two jets,  $m_{jj} > 500 \text{ GeV}$ ,  $\Delta R(j, l) > 0.3$ .

aQGC phase space:

- $|\Delta\Phi(W, Z)| > 2$  and  $\sum |p_T^l| > 250 \text{ GeV}$  required in VBS phase space.

Measured electroweak  $WZjj$  production is  $0.29^{+0.14}_{-0.12}(\text{stat})^{+0.09}_{-0.10}(\text{syst}) \text{ fb}$ .

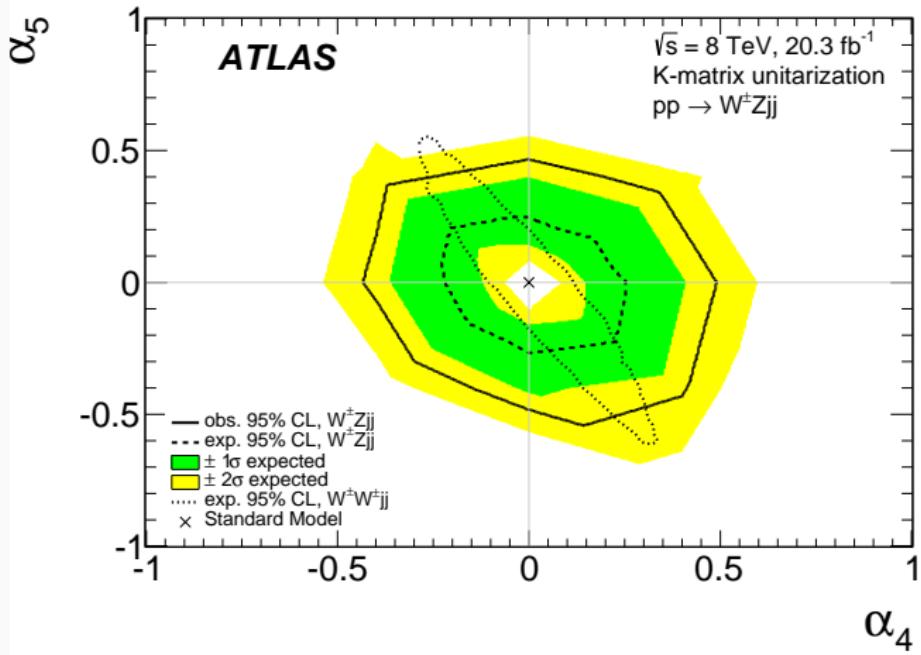
SM prediction is  $0.13 \pm 0.01 \text{ fb}$  at NLO.



95% CL upper limit on $\sigma_{W^\pm Zjj-\text{EW} \rightarrow l'\nu ll}^{\text{fid.}} [\text{fb}]$		
VBS only	VBS + $tZj$	
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm 1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm 2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]
aQGC phase space		
Observed	0.25	0.25
Expected	0.13	0.13
$\pm 1\sigma$ Expected	[0.08 ; 0.20]	[0.08 ; 0.20]
$\pm 2\sigma$ Expected	[0.04 ; 0.28]	[0.06 ; 0.28]

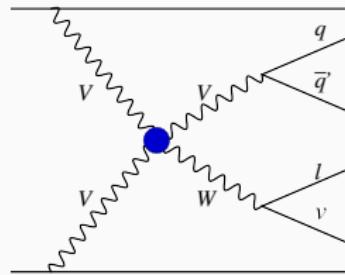
# $W^\pm Z$ aQGCs

- Constraints are derived on the aQGCs from the WWZZ vertex.



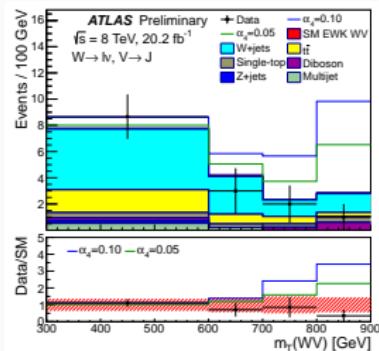
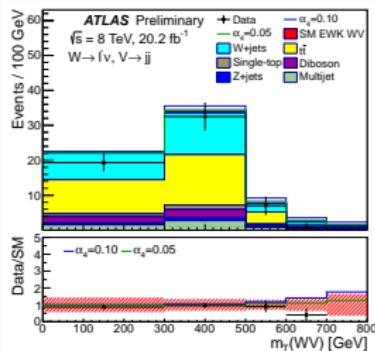
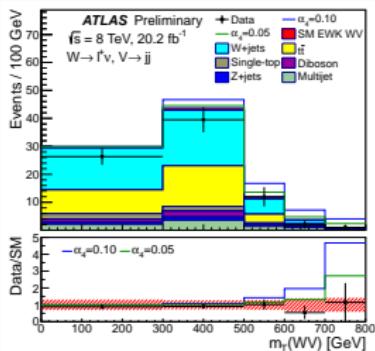
# WVjj Production

- Preliminary results in July 2016.
- Better sensitivity to aQGCs due to large branch ratio.
- Less sensitivity to SM signal due to large background.
- $V \rightarrow jj$  reconstructed as either two jets or one merged jet.
  - Resolved selection:
    - Four small radius (0.4) jets.
  - Merged selection:
    - Two small radius (0.4) jets.
    - One large radius(1.2) jet, jet substructure consistent with the two-body decay.
- The resolved region is further categorized by  $W \rightarrow l^+\nu$  and  $W \rightarrow l^-\nu$ .



# WVjj Production

- The transverse mass of WV is used to search for aQGCs.
- Merged region significantly improves the aQGCs sensitivity.

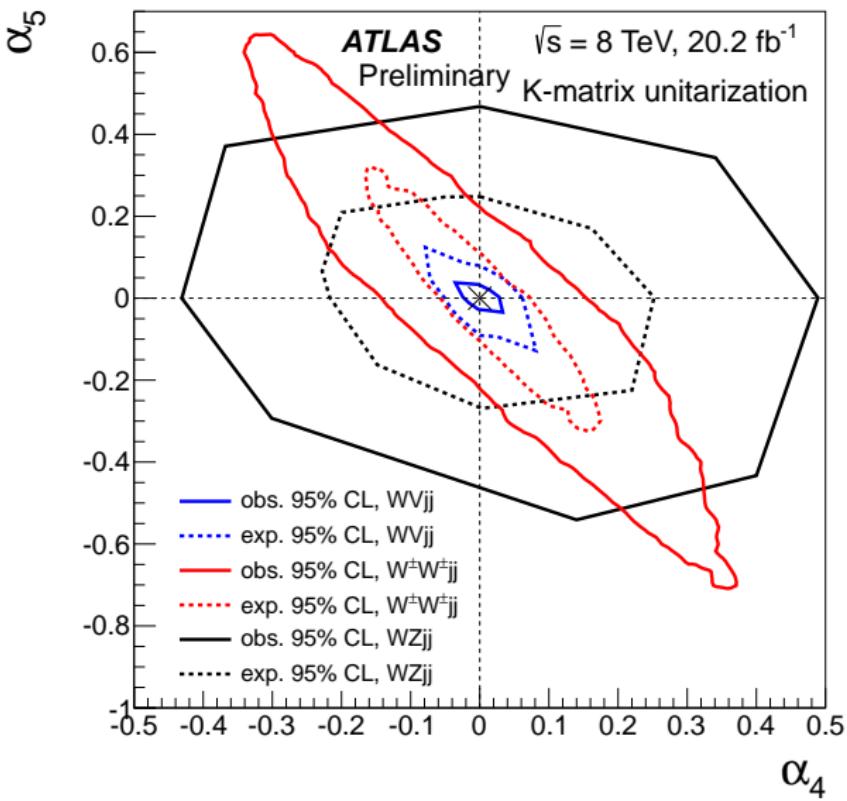


$W \rightarrow l^+\nu, V \rightarrow jj$   
Resolved region

$W \rightarrow l^-\nu, V \rightarrow jj$   
Resolved region

$W \rightarrow l\nu, V \rightarrow jj$   
Merged region

# WVjj aQGCs



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

$\sqrt{s} = 8 \text{ TeV}$ ,  $\int L = 20.2 \text{ fb}^{-1}$ , [arXiv:1607.03745](#)

Goals:

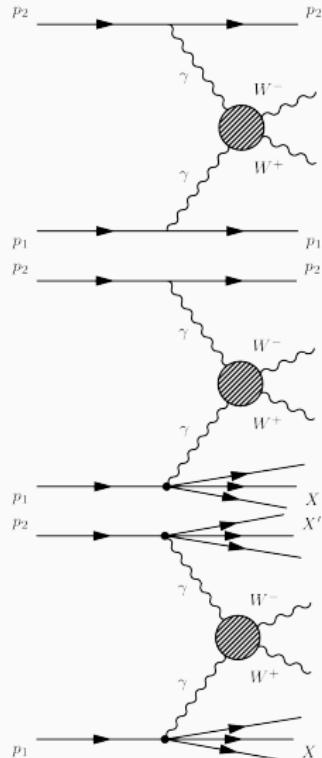
- Search for exclusively produced W boson pairs in the process  $pp(\gamma\gamma) \rightarrow pW^+W^-p$ .
- Sensitive to new physics via aQGC.

Signal:

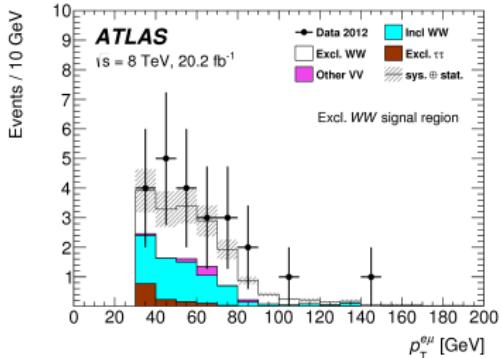
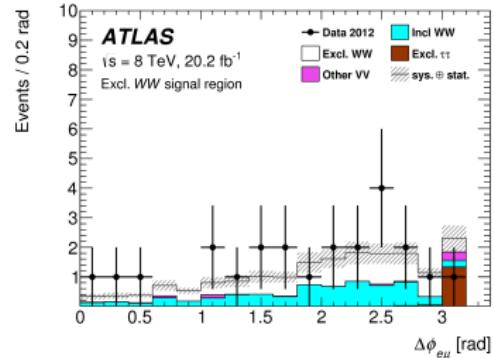
- Opposite charged  $e^\pm \mu^\mp$  leptons with  $p_T^1 > 25 \text{ GeV}$  and  $p_T^2 > 20 \text{ GeV}$ ,  $m_{ll} > 20 \text{ GeV}$ ,  $p_T^{e\mu} > 30 \text{ GeV}$ , exclusivity selection requires no extra tracks within 1 mm of primary vertex.
- Additional  $p_T^{e\mu} > 120 \text{ GeV}$  requirement for aQGCs study.

Main Backgrounds:

- Inclusive  $W^+W^- (\sim 70\%)$ .
- $\gamma\gamma \rightarrow \tau^+\tau^- (\sim 15\%)$ .

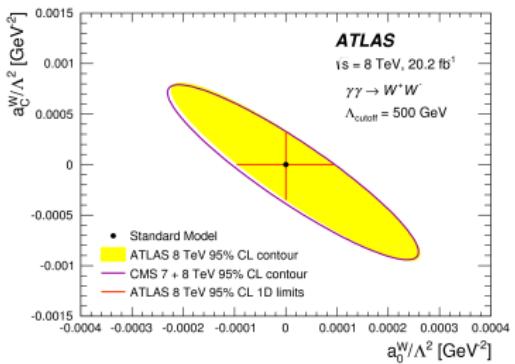
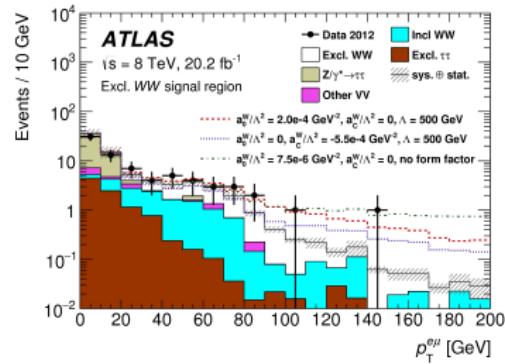


# Exclusive $\gamma\gamma \rightarrow W^+ W^-$ Cross Section



- Observed signal significance is  $3.0\sigma$ .
- $\sigma_{\gamma\gamma \rightarrow W^+ W^- \rightarrow e^\pm \mu^\mp}^{\text{Measured}} = 6.9 \pm 2.2(\text{stat}) \pm 1.4(\text{syst}) \text{ fb.}$
- $\sigma_{\gamma\gamma \rightarrow W^+ W^- \rightarrow e^\pm \mu^\mp}^{\text{Predicted}} = 4.4 \pm 0.3 \text{ fb.}$

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



- The 95% CL limits on the couplings  $\alpha_0^W/\Lambda^2$  and  $\alpha_C^W/\Lambda^2$ .

# $W\gamma\gamma$ Production

$\sqrt{s} = 8 \text{ TeV}$ ,  $\int L = 20.3 \text{ fb}^{-1}$ , [arXiv:1503.03243](#)

Goals:

- First triboson measurement in ATLAS.
- Inclusive ( $N_{jets} \geq 0$ ) and exclusive ( $N_{jets} = 0$ ) regions.
- Sensitive to new physics via anomalous gauge couplings.

Signature:

- One isolated lepton and high missing energy.
- Two isolated photons.

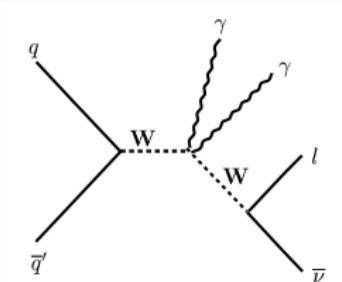
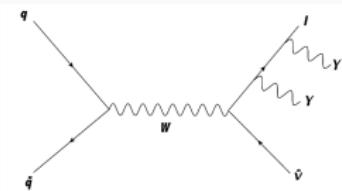
Definition of the fiducial region

$$p_T^\ell > 20 \text{ GeV}, p_T^\nu > 25 \text{ GeV}, |\eta_\ell| < 2.5$$

$$m_T > 40 \text{ GeV}$$

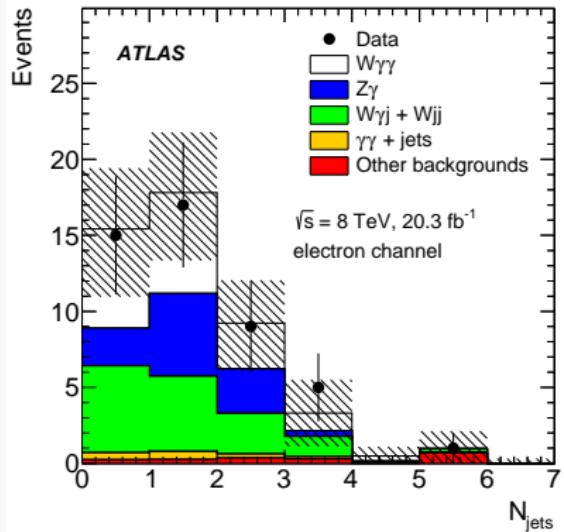
$$E_T^\gamma > 20 \text{ GeV}, |\eta^\gamma| < 2.37, \text{iso. fraction } \epsilon_h^p < 0.5$$
$$\Delta R(\ell, \gamma) > 0.7, \Delta R(\gamma, \gamma) > 0.4, \Delta R(\ell/\gamma, \text{jet}) > 0.3$$

Exclusive: no anti- $k_t$  jets with  $p_T^{\text{jet}} > 30 \text{ GeV}, |\eta^{\text{jet}}| < 4.4$

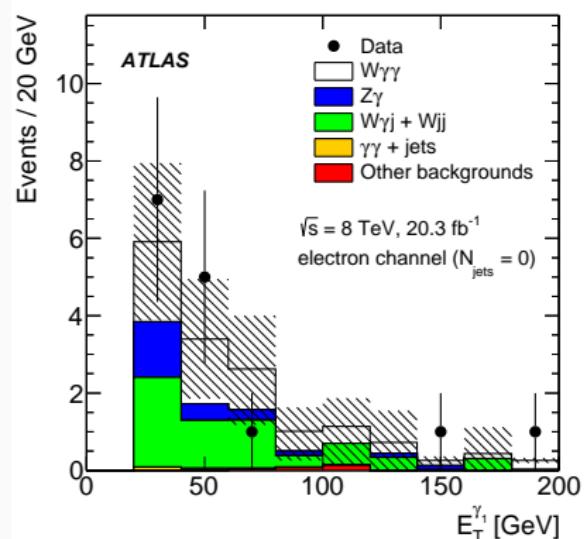


Main backgrounds are  $Z\gamma$  and  $W\gamma j + Wjj$  due to fake object(Data driven).

# $W\gamma\gamma$ Production



Number of jets distribution



Leading photon ET in the Njet=0 region

# $W\gamma\gamma$ Cross Section

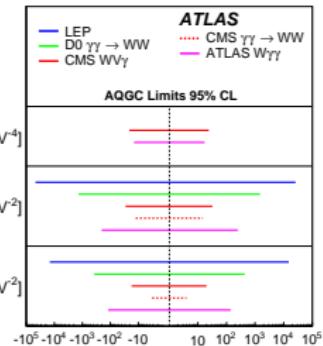
- Fiducial cross sections are obtained from a maximum likelihood fit.
- The largest uncertainty is from the data-driven background estimation.
- $3\sigma$  significance observed for  $W\gamma\gamma$ .

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

# $W\gamma\gamma$ aQGCs

- aQGC limits set on dimension 8 operators.
- Measurement in exclusive region with additional requirement of  $m_{\gamma\gamma} > 300\text{GeV}$  is used to study the aQGCs.
- Form factor  $(1 + \frac{s}{\Lambda_{FF}^2})^{-n}$

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



# $Z\gamma\gamma$ Production

$\sqrt{s} = 8 \text{ TeV}$ ,  $\int L = 20.3 \text{ fb}^{-1}$ , [arXiv:1604.05232](#)

Goals:

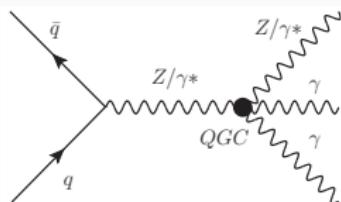
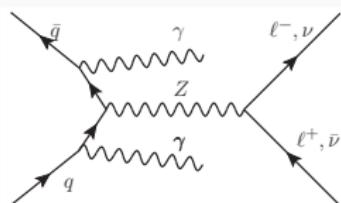
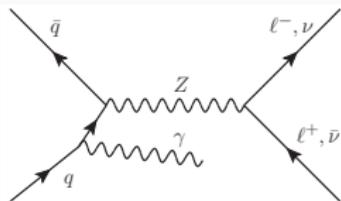
- Measure the production cross sections in the inclusive ( $N_{jets} \geq 0$ ) and exclusive ( $N_{jets} = 0$ ) regions.
- Sensitive to new physics via aQGC.

Signal:

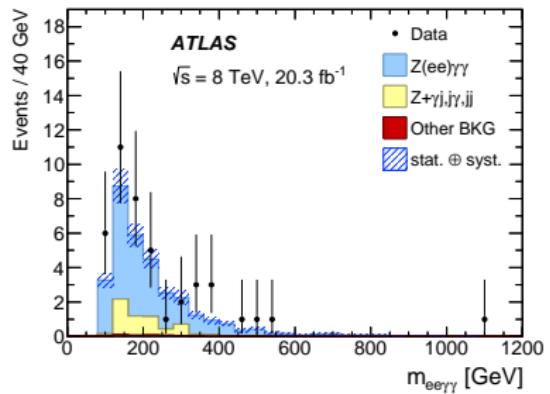
- Z boson decay leptonically ( $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\nu^+\nu^-$ ).
- Two isolated high energy photons.

Backgrounds:

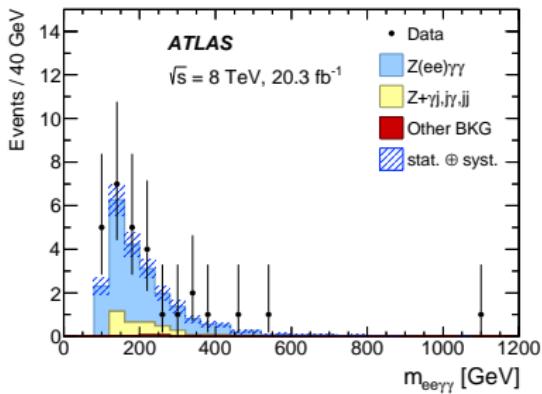
- Main backgrounds are  $Z + \gamma j$  and  $Z + jets$  from fake object (Data-driven).



# $Z\gamma\gamma$ Production



The four-body invariant mass distributions from inclusive region of ee channel.



The four-body invariant mass distributions from exclusive region of ee channel.

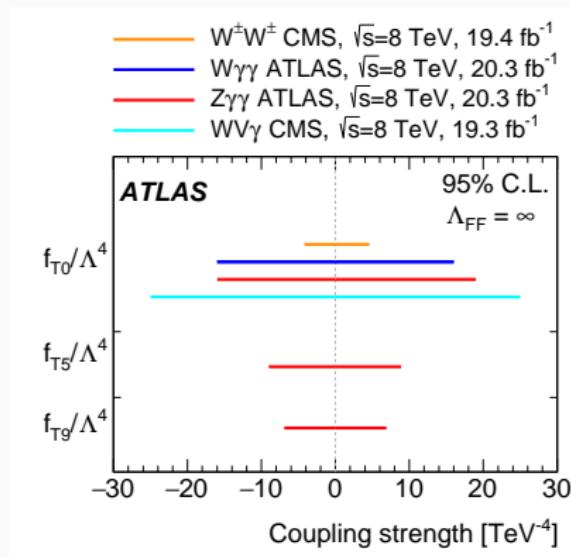
# $Z\gamma\gamma$ Cross Section

- Observed significance of  $ll\gamma\gamma$  is  $6.3\sigma$  for inclusive region and  $6.0\sigma$  for exclusive region.
- Measured cross sections are compatible with the MCFM(NLO) predictions.
  - Within  $1.7\sigma$  for inclusive region.
  - Within  $0.9\sigma$  for exclusive region.

Channel	Measurement [fb]	MCFM Prediction [fb]
$N_{\text{jets}} \geq 0$		
$e^+e^-\gamma\gamma$	$6.2^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	
$\mu^+\mu^-\gamma\gamma$	$3.83^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$
$\ell^+\ell^-\gamma\gamma$	$5.07^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$2.5^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$
$N_{\text{jets}} = 0$		
$e^+e^-\gamma\gamma$	$4.6^{+1.0}_{-0.9}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \pm 0.1(\text{lumi.})$	
$\mu^+\mu^-\gamma\gamma$	$2.38^{+0.77}_{-0.67}(\text{stat.})^{+0.33}_{-0.32}(\text{syst.})^{+0.05}_{-0.04}(\text{lumi.})$	$2.91^{+0.23}_{-0.12}$
$\ell^+\ell^-\gamma\gamma$	$3.48^{+0.61}_{-0.56}(\text{stat.})^{+0.29}_{-0.25}(\text{syst.}) \pm 0.07(\text{lumi.})$	
$\nu\bar{\nu}\gamma\gamma$	$1.18^{+0.52}_{-0.44}(\text{stat.})^{+0.48}_{-0.49}(\text{syst.}) \pm 0.02(\text{lumi.})$	$0.395^{+0.049}_{-0.037}$

# $Z\gamma\gamma$ aQGCs

- Measurement in the exclusive channels with additional requirement of  $m_{\gamma\gamma} > 200(\ell\ell\gamma\gamma)$  and  $300(\nu\nu\gamma\gamma)$  GeV is used to study the aQGCs.
- Sensitivity dominated by  $\nu\nu\gamma\gamma$  channel.



$\sqrt{s} = 8 \text{ TeV}$ ,  $\int L = 20.3 \text{ fb}^{-1}$

Goals:

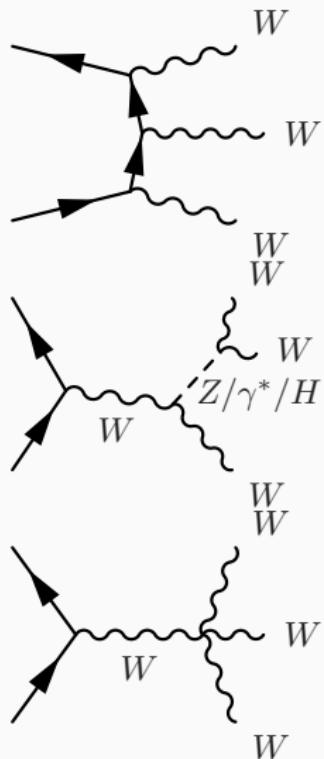
- Search for triboson  $W^\pm W^\pm W^\mp$  production.
- Sensitive to new physics via aQGC.

Signal:

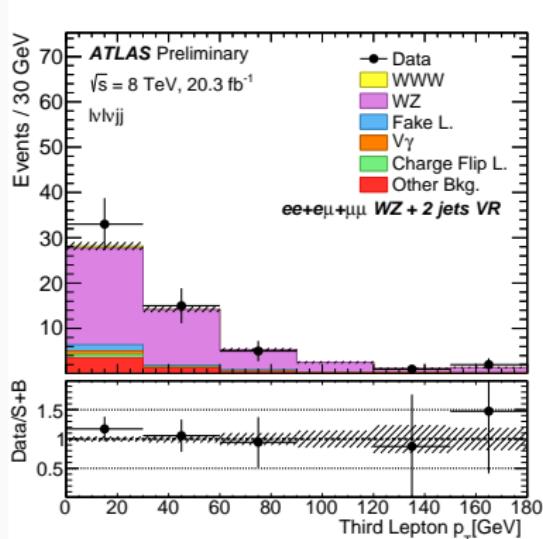
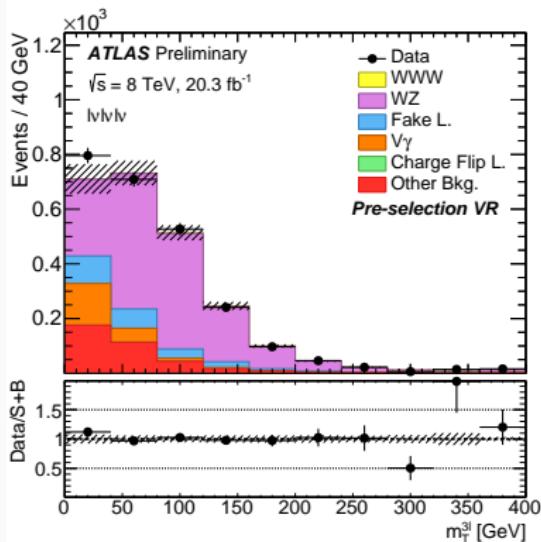
- $W^\pm W^\pm W^\mp \rightarrow l^\pm \nu l^\pm \nu l^\mp \nu$ .
- $W^\pm W^\pm W^\mp \rightarrow l^\pm \nu l^\pm \nu jj$  ( $l = e, \mu$ ).

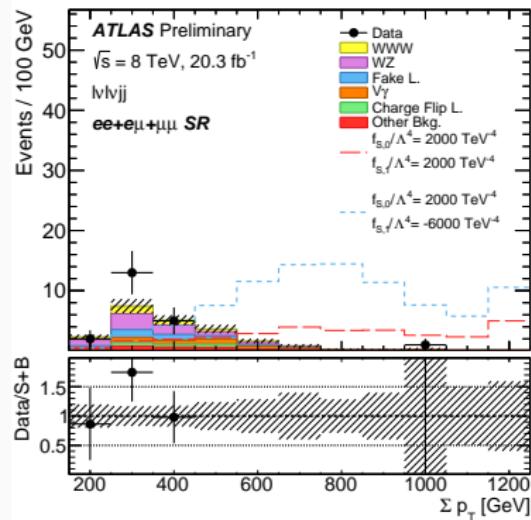
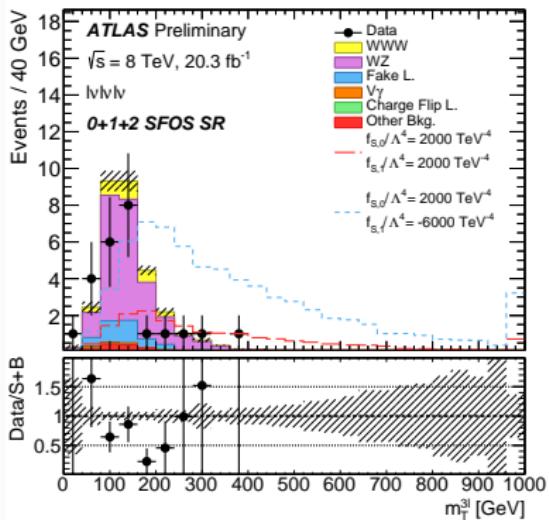
Backgrounds:

- $WZ/\gamma^*$ ,  $W\gamma + \text{jets}$  or  $Z\gamma + \text{jets}$  (MC).
- Lepton's charge mis-ID (Data-driven).
- Fake leptons originated from jets or hadronic decays (Data driven).



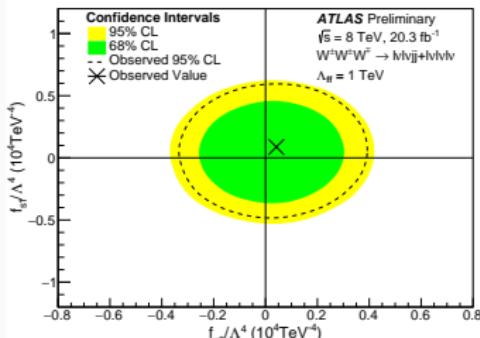
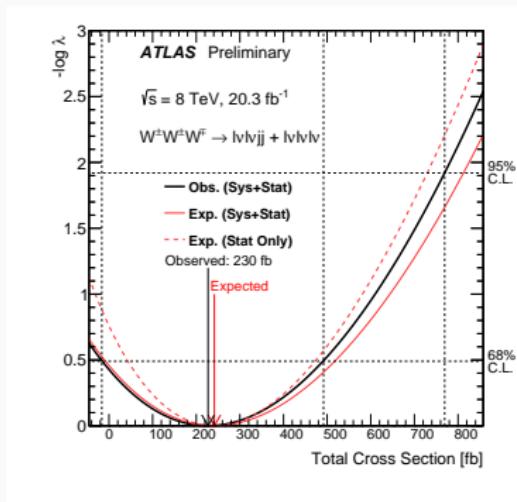
- Distributions in validation region for  $l\nu l\nu l\nu$  and  $l\nu l\nu jj$  channels.
- $m_T^{3l}$  for  $l\nu l\nu l\nu$  channel(Left).
- Third lepton pT for  $l\nu l\nu jj$  channel(Right).





# WWW Cross Section and aQGCs

- No significant deviation from SM observed.
  - Total and fiducial cross-sections extracted, only  $\sim 1$  sigma significance.
- aQGCs limits with 95%CL set.



# Summary

- Results of VBS, Exclusive WW and Tri-boson analysis presented.
- Overall good agreement with SM expectations!

