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

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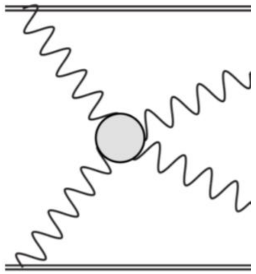
Outline

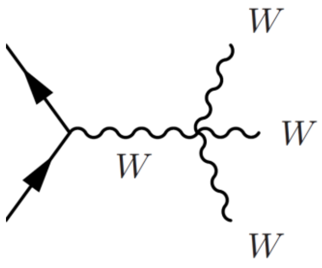
- Physics motivation
- VBS final states
  - Zγ + 2jets
- Tri-boson final states
  - WWW
  - WVγ (V = W, Z)
- Summary

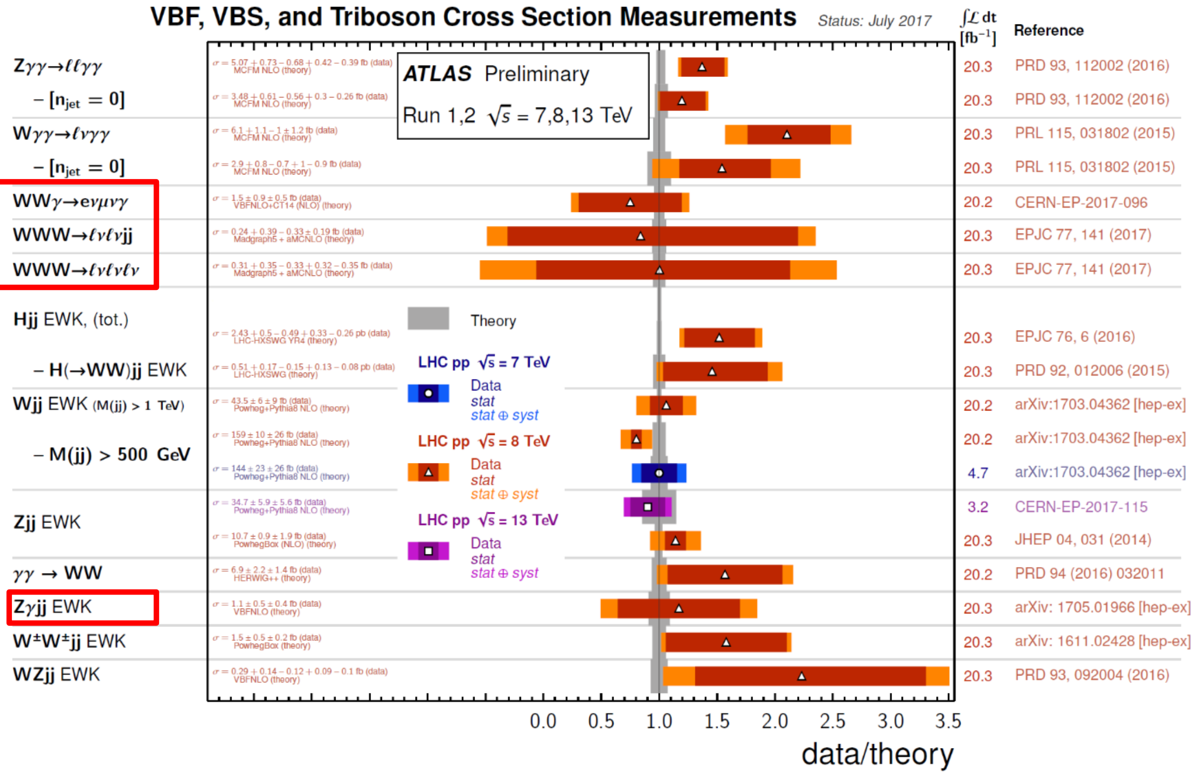
- Results with 20.2 fb^{-1}, 8 TeV dataset

Physics Motivation

- Vector Boson Scattering (VBS) is a key process to probe the mechanism of electroweak symmetry breaking (EWSB)
- Triboson final state provides another way to test QGC vertex
- Involving Quartic Gauge Couplings (QGCs) which is sensitive to new physics
  - Only charged QGCs allowed at Standard Model (SM) tree-level (WWWW, WWZZ, WWZγ, WWγγ)
  - Constraint on aQGCs
  - Probe new physics through deviations from SM

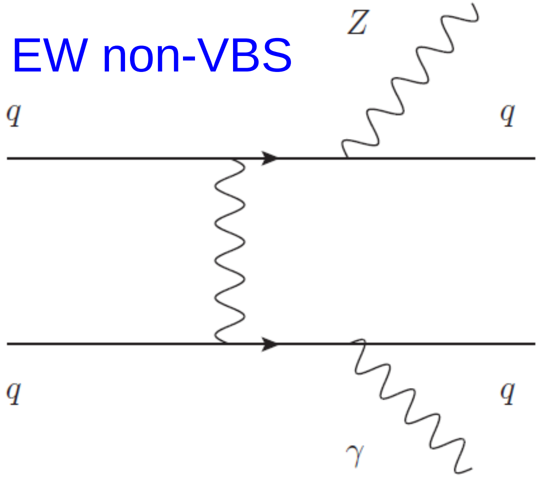




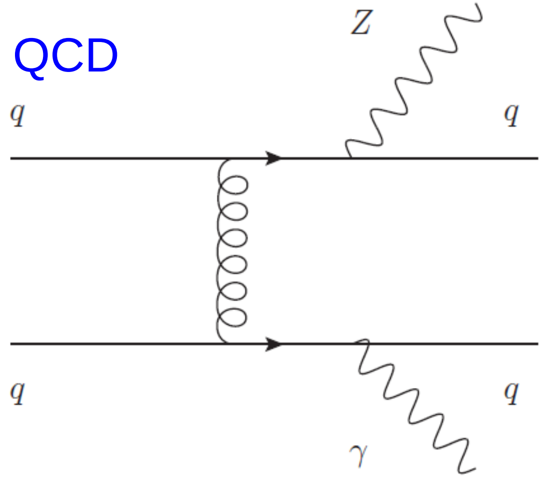


VBS: Zγ + 2jets

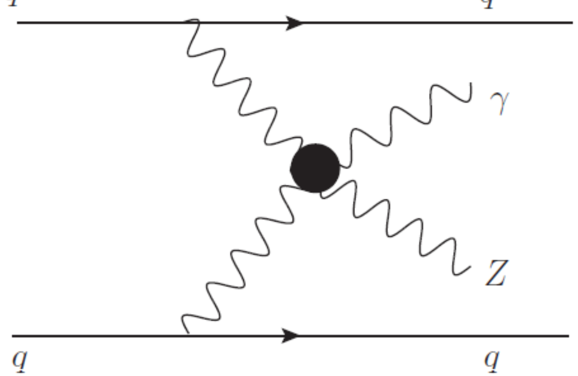
EW non-VBS



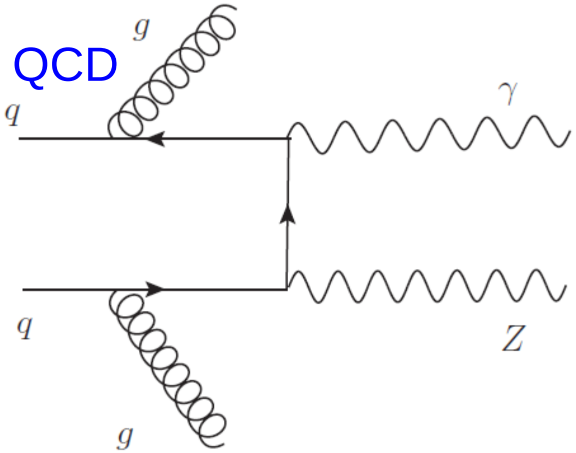
QCD



EW VBS



QCD



- ✓ Z → leptons/neutrinos
- ✓ Dominant background
  - ✓ Charged-lepton channel: Z+jets, with jets faking photons
  - ✓ Neutrino channel: W(lν)γ + jets

arXiv:1705.01966

VBS: Event Selections

Charged-lepton channel

- ✓ Isolated electron, muon and photon
- ✓ Two same-flavor, opposite-sign leptons
- ✓ At least two jets with large rapidity difference
- ✓ $m_{ll} > 40$ GeV
- ✓ $m_{ll} + m_{ll\gamma} > 182$ GeV to reduce Final State Radiation (FSR)

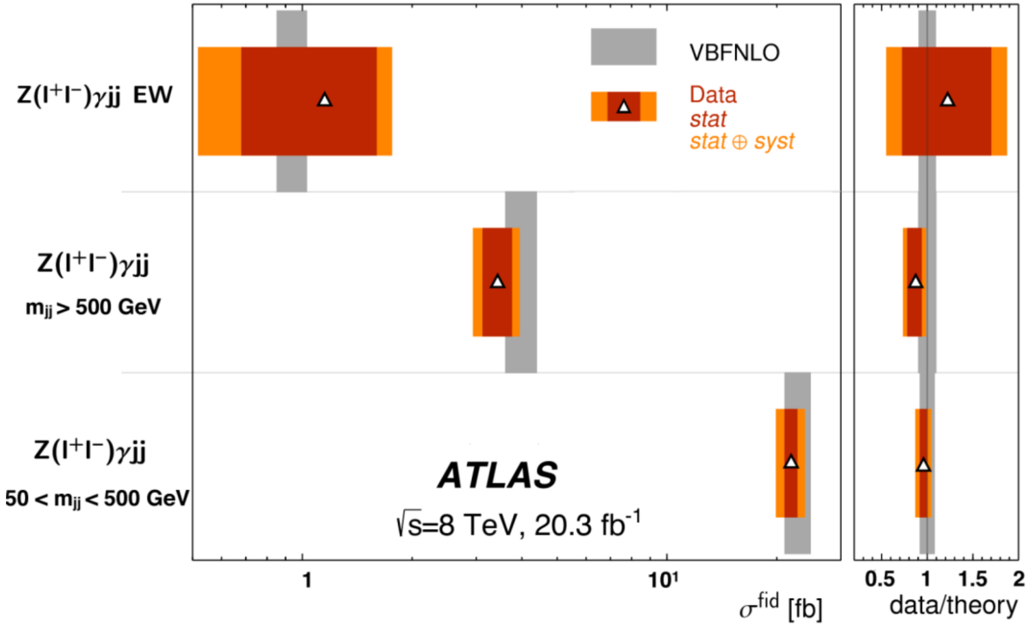
Neutrino channel

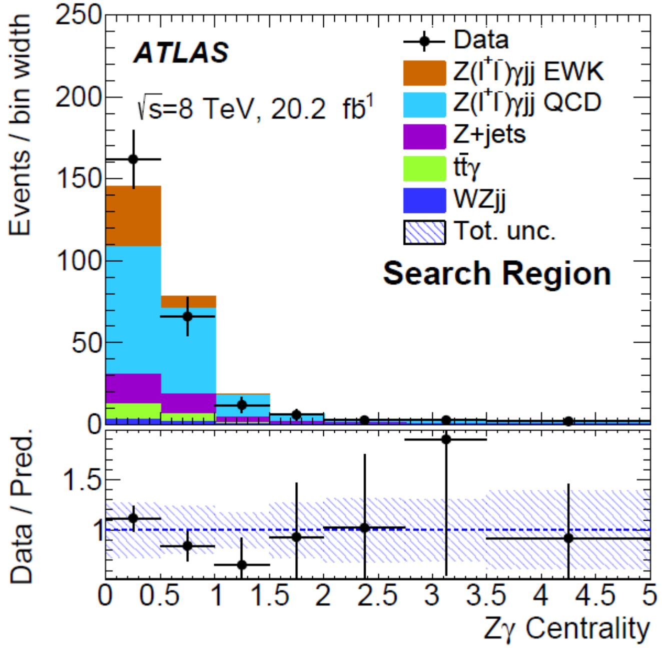
- ✓ Missing $E_T > 100$ GeV
- ✓ Photon $E_T > 150$ GeV
- ✓ At least two jets with large rapidity difference
- ✓ Lepton veto to reduce $W(l\nu)\gamma$ + jets
- ✓ Event level topology cut to suppress γ + jets and $W(e\nu)$ + jets

- ✓ Search region: $m_{jj} > 500$ GeV to study EWK $Z\gamma$ + 2jets production and measure the combined cross sections of QCD+EWK
- ✓ aQGC region: $m_{jj} > 500$ GeV and $E_T^{\gamma} > 250$ (150) GeV optimized for sensitivity to aQGC for charged-lepton (neutrino) channel and measure the combined cross sections of QCD+EWK

VBS: Cross-section Measurements

- A fit to the centrality is used to extract the cross sections of EWK and QCD processes in search region, in the charged-lepton channel
  - ✓ Expected significance: 1.8σ, for EWK production
  - ✓ Observed significance: 2.0σ, for EWK production





$$\zeta \equiv \left|\frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}}\right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$

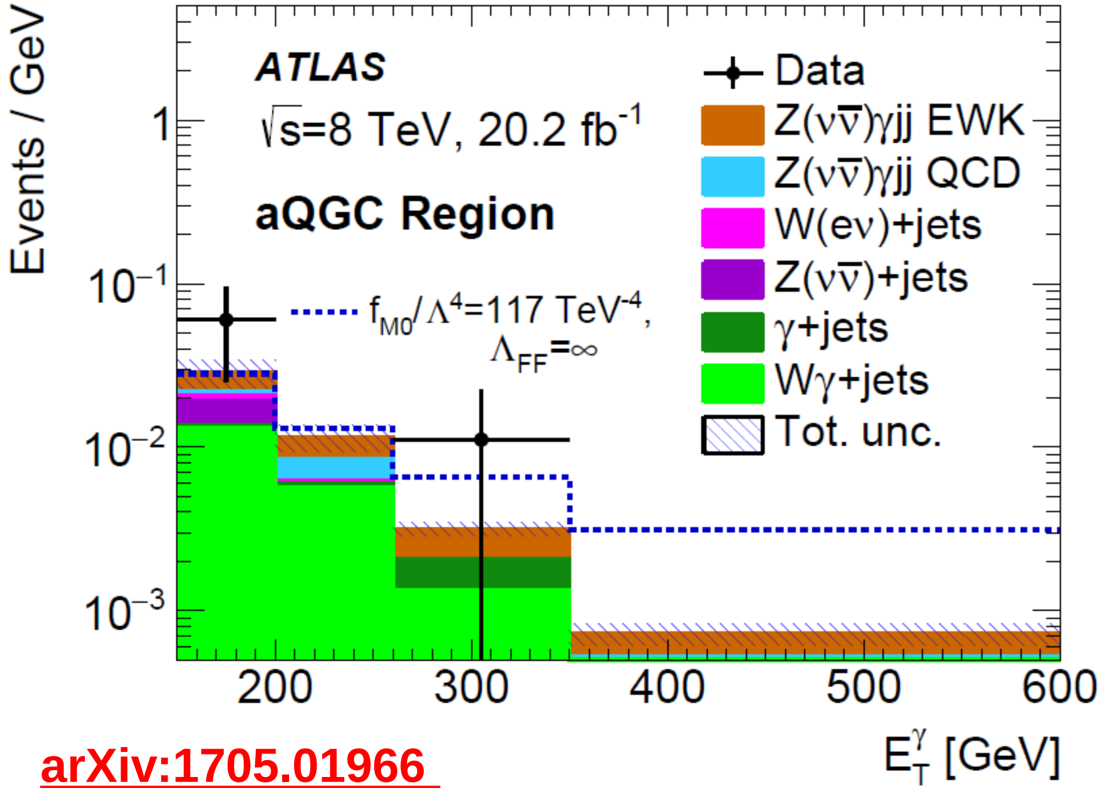
arXiv:1705.01966

VBS: aQGCs

- aQGC optimized region is defined with further $E_T^\gamma > 250$ (150) GeV cut for charged-lepton (neutrino) channel

✓ Better expected limit from neutrino channel
✓ Improved by 10-30% if combined with charged-lepton channel

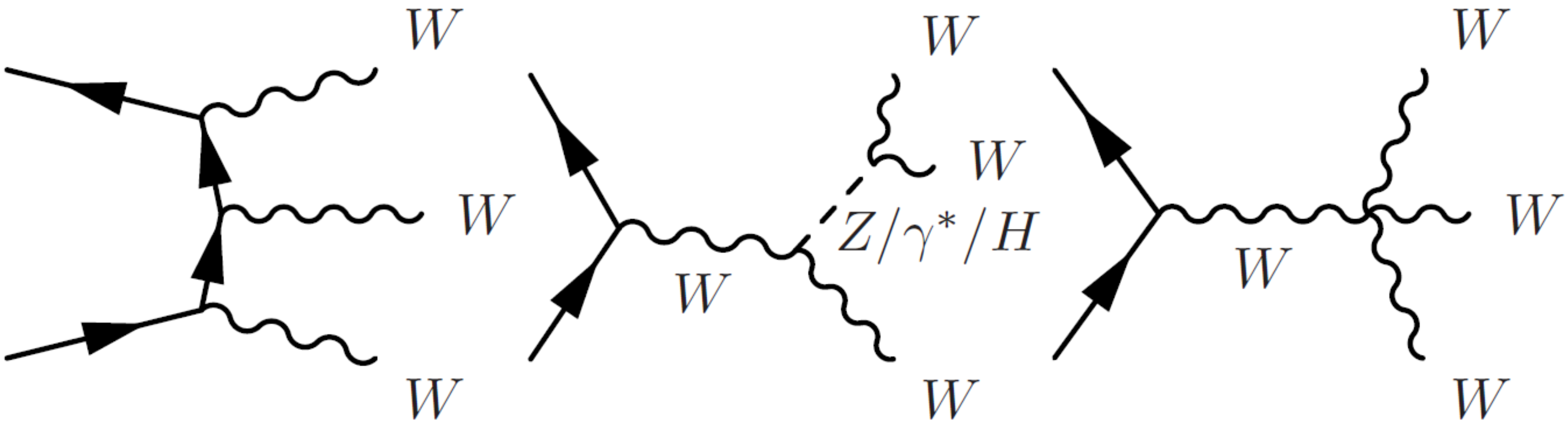
	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	$[-3.9, 3.9]$	$[-2.7, 2.8]$
	f_{T8}/Λ^4	$[-1.8, 1.8]$	$[-1.3, 1.3]$
	f_{T0}/Λ^4	$[-3.4, 2.9]$	$[-3.0, 2.3]$
	f_{M0}/Λ^4	$[-76, 69]$	$[-66, 58]$
	f_{M1}/Λ^4	$[-147, 150]$	$[-123, 126]$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



arXiv:1705.01966

Triboson: WWW

$$W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu\ell^{\mp}\nu \text{ and } W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$$



LO processes

Dominant background from WZ/γ* + jets process

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WWW: Event Selections

Split based on number of same-flavor, opposite-sign lepton (SFOS) pairs

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

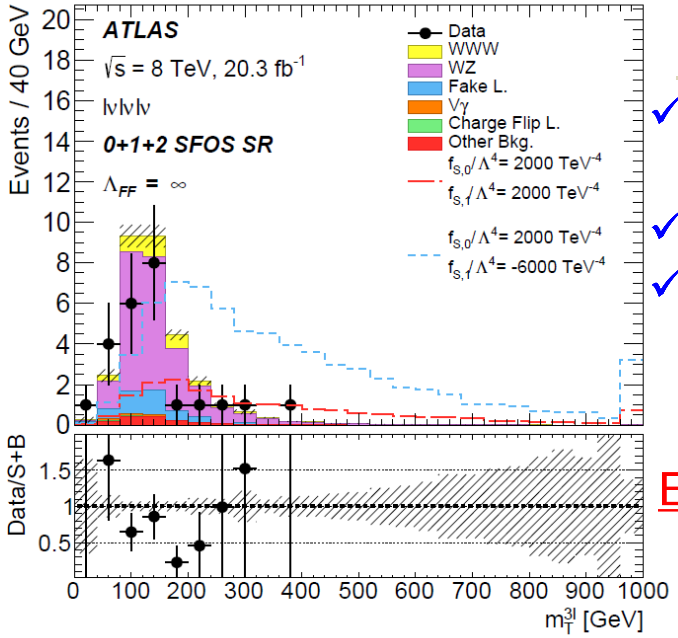
Split based on lepton flavor

$\ell\nu\ell\nu jj$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
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 $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
E_T^{miss}	$E_T^{miss} > 55$ GeV		-
m_{jj}	65 GeV $< m_{jj} <$ 105 GeV		
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$		
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV	-	
Third-lepton veto	No third lepton with $p_T > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified b–jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$		

Same-sign channel has much better Drell-Yan suppression

WWW: Cross-section Measurements

- Prediction agrees with observed data in all 6 signal regions
- Observed (expected) significance of a positive signal is 0.96σ (1.05σ), combining all channels (mostly from 0-SFOS and μμ channel)



- ✓ Contributions from aQGCs also shown in plots
- ✓ Non-unitarized case ($\Lambda_{FF} = \infty$)
- ✓ Two different sets of $f_{S,0}/\Lambda^4$ and $f_{S,1}/\Lambda^4$ configurations

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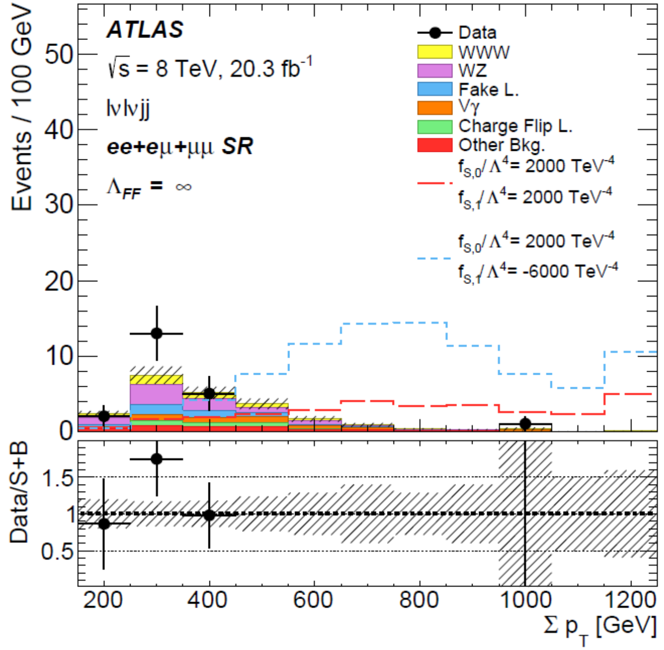
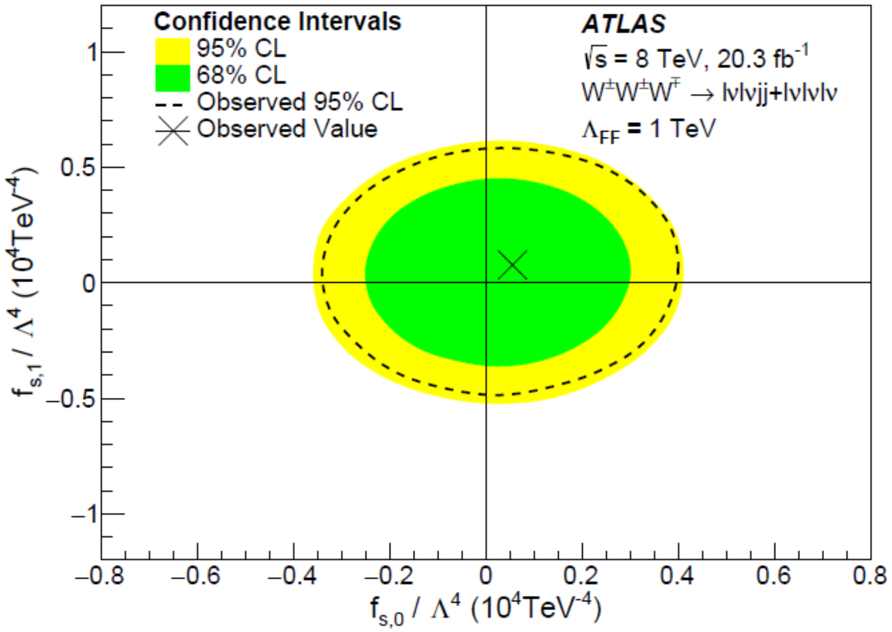
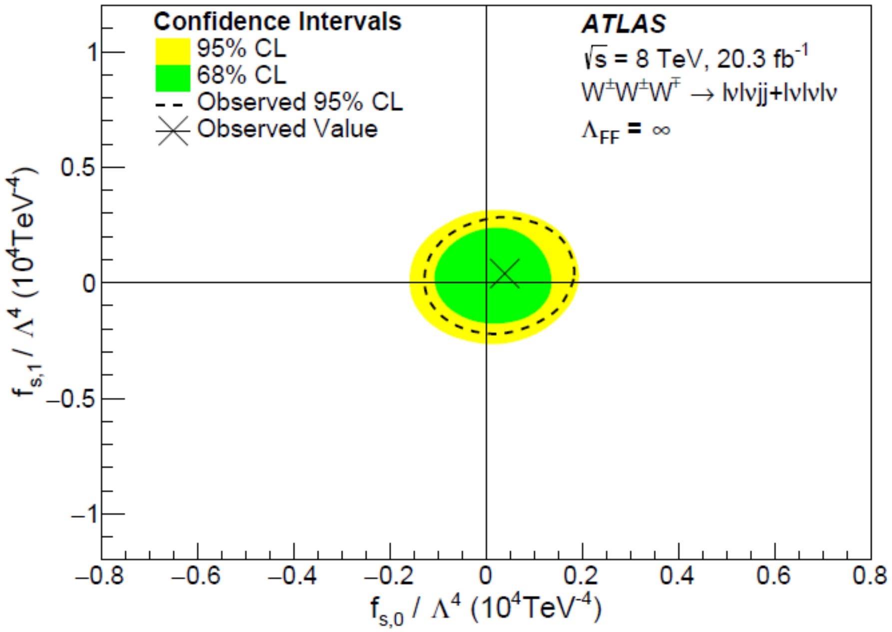


		Cross section [fb] Theory	Cross section [fb] Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.)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

WWW: aQGCs

- aQGC events generated with VBFNLO at LO and scaled to NLO prediction





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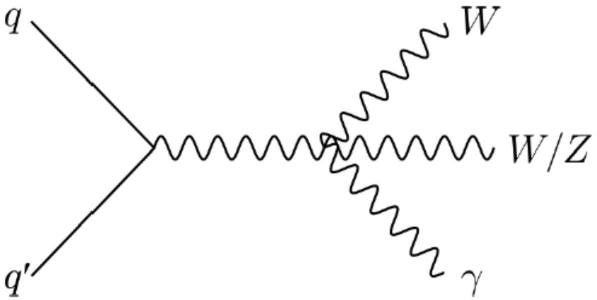
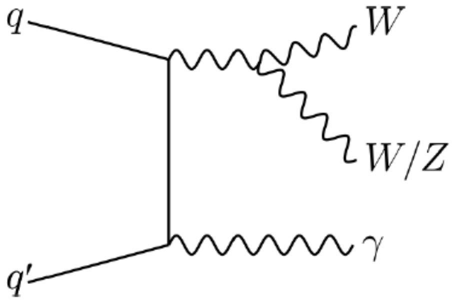
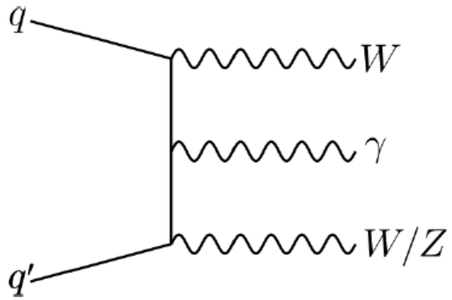
Triboson: WVγ (V = W, Z)







Produced through QGC

Produced through radiation

Fully leptonic channel and semi-leptonic channel

- ✓ Dominant background for leptonic channel: $t\bar{t}\gamma$
- ✓ Dominant background for semi-leptonic channel: Wγ* + jets

STDM-2016-05

WVγ: Cross-section Measurements

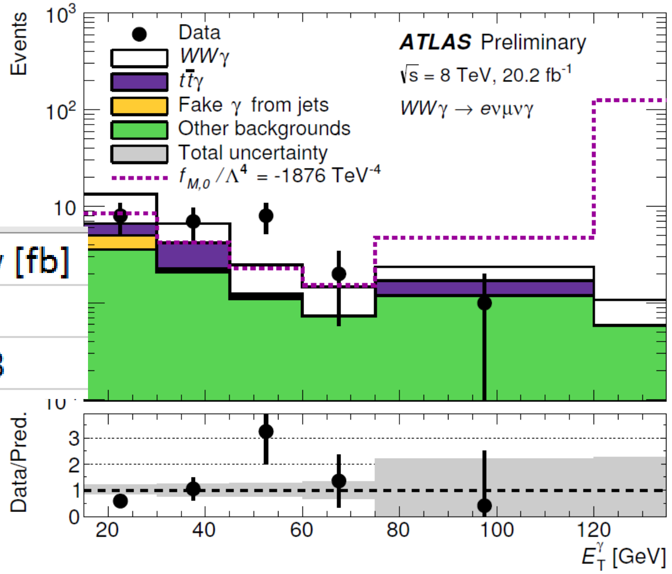
eνμνγ	lνjjγ
1 electron and 1 muon Opposite charge	1 electron or 1 muon
No 3rd lepton	No 2nd lepton
At least 1 isolated photon	
0 jet	At least 2 jets, 0 b-jet
Missing E_T > 15 GeV $m_{e\mu}$ > 50 GeV	Missing E_T > 30 GeV m_T > 30 GeV

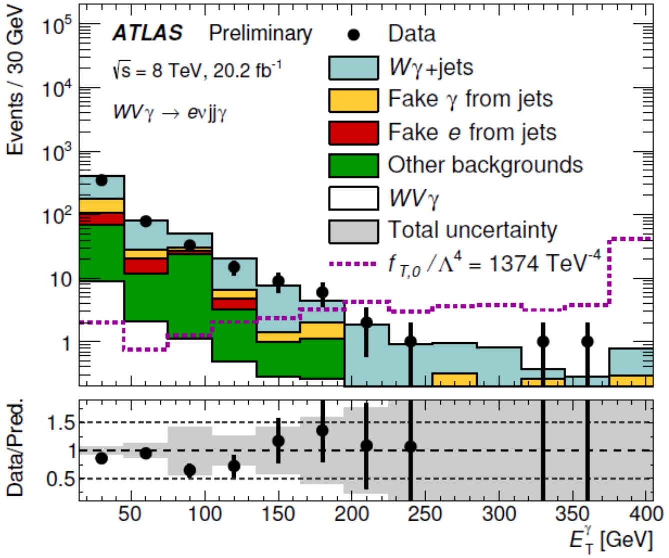
Upper limit		Observed limit [fb]	Expected limit [fb]	Theory [fb]
Fully leptonic	eνμνγ	3.7	2.1 + 0.9 - 0.6	2
Semileptonic	lνjjγ	5.7	8.4 + 3.4 - 2.4	2.3

Prediction from VBFNLO at particle level

- ✓ Fiducial cross section measured in fully leptonic channel
- ✓ Expected significance: 1.6σ
- ✓ Observed significance: 1.4σ

$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = (1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.}))\ \text{fb}$$





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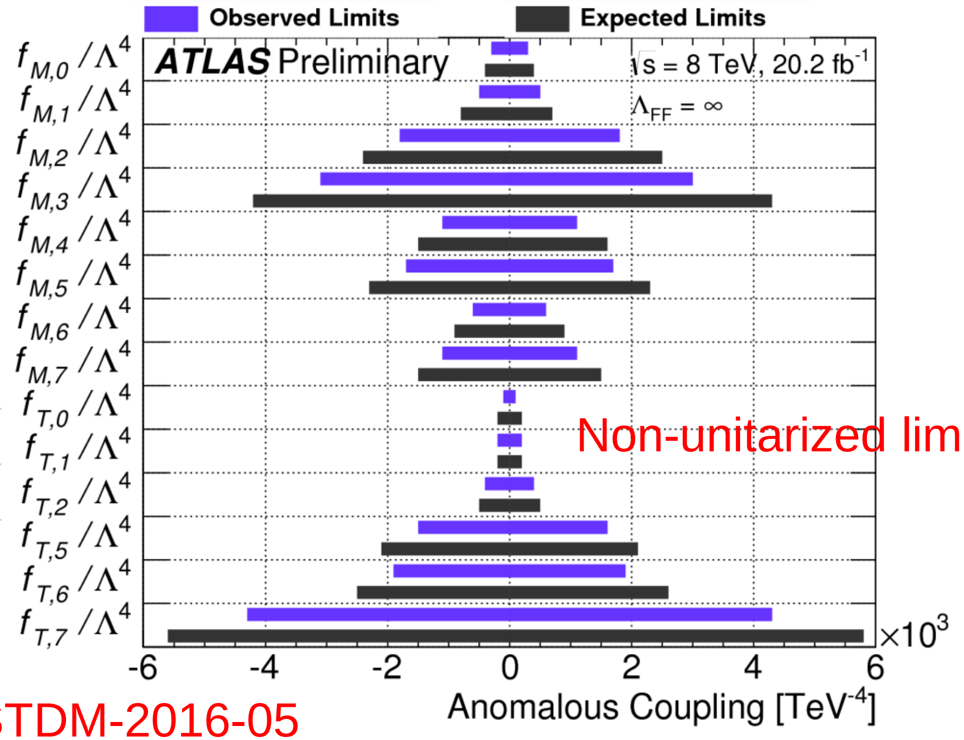
WVγ: aQGCs

- Optimized fiducial region defined for aQGCs and search for new physics by increasing photon E_T cut (E_T > 120 GeV for fully leptonic analysis, E_T > 200 GeV for semi-leptonic analysis)



Non-unitarized limits

Upper limits

		Observed limit [fb]	Expected limit [fb]	Theory [fb]
Fully leptonic	eνμνγ	0.3	0.3 + 0.3 - 0.1	0.076
Semileptonic	lνjjγ	0.9	0.9 + 0.3 - 0.2	0.054

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Summary

- Recent ATLAS results for VBS, Triboson and aQGCs
- Limit set on cross-sections and compared with NLO SM predictions
- Limits set on aQGC parameters modelled by dimension-8 operators

- Will benefit from Run 2 data for VBS/Triboson cross-section measurements and aQGC limits

backup

aQGC

- Effective operators approach

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Three types of dimension-8 operators
  - Scalar: S0, S1, S2
  - Tensor: T0 – T9
  - Mixed: M0 – M7

Michael Rauch, arxiv:1610.08420
O. J. P. Eboli, M. C. Gonzalez-Garcia, arXiv:1604.03555

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

Zγ + 2jets: Particle/Parton Level Event Selections

Charged-lepton channel phase-space region definitions

Objects	Particle- (Parton-) level selection
Leptons	$p_{\mathrm{T}}^{\ell} > 25$ GeV and $\lvert\eta^{\ell}\rvert < 2.5$ Dressed leptons, OS charge
Photon (kinematics)	$E_{\mathrm{T}}^{\gamma} > 15$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell,\gamma) > 0.4$
Photon (isolation)	$E_{\mathrm{T}}^{\mathrm{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$ (no isolation)
FSR cut	$m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $m_{\ell\ell} > 40$ GeV
Particle jets (Outgoing partons) (j = jets) (p = outgoing quarks or gluons)	At least two jets (outgoing partons) $E_{\mathrm{T}}^{j(p)} > 30$ GeV, $\lvert\eta^{j(p)}\rvert < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$

Neutrino channel

Objects	Particle- (Parton-) level selection
Neutrinos	$E_{\mathrm{T}}^{\nu\bar{\nu}} > 100$ GeV
Photon (kinematics)	$E_{\mathrm{T}}^{\gamma} > 150$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell,\gamma) > 0.4$
Photon (isolation)	$E_{\mathrm{T}}^{\mathrm{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$
Generator-level jets (Outgoing quarks) ($pp \to Z\gamma qq$)	At least two jets (quarks) $E_{\mathrm{T}}^{j(q)} > 30$ GeV, $\lvert\eta^{j(q)}\rvert < 4.5$ $\Delta R(\gamma, j(q)) > 0.4$
Event kinematic selection	$\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, \gamma jj(qq))\rvert > \frac{3\pi}{4}$ $\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, \gamma)\rvert > \frac{\pi}{2}$ $\lvert\Delta\phi(E_{\mathrm{T}}^{\nu\bar{\nu}}, j(q))\rvert > 1$ $E_{\mathrm{T}}^{\gamma} > 150$ GeV $\lvert\Delta y_{jj(qq)}\rvert > 2.5$ $\zeta_{\gamma} < 0.3$ $p_{\mathrm{T}}^{\mathrm{balance}} < 0.1$ $m_{jj(qq)} > 600$ GeV

Zγ + 2jets: Systematic Uncertainties

Table 6: Summary of the main relative uncertainties in cross-section measurements presented in this paper.

Source of uncertainty	EWK [%]	Total (EWK+QCD) [%] SR	CR
Statistical	40	9	4
Jet energy scale	36	9	4
Theory	10	5	4
All other	8	5	6
Total systematic	38	11	8

WWW: Systematic Uncertainties

Table 4: The effect of the various systematic uncertainties on the total signal and background yields (in percent) for both channels.

Source of Uncertainty	$\ell\nu\ell\nu\ell\nu$		$\ell\nu\ell\nu jj$	
	Signal [%]	Background [%]	Signal [%]	Background [%]
Lepton ID, E_T/p_T scale and resolution	1.6	1.8	2.1	3.3
E_T^{miss} modelling	1.1	1.4	0.7	1.8
b-jet identification	0.3	0.3	2.2	2.2
Jet E_T scale and resolution	2.3	2.8	21	15
Fake-lepton background	0	13	0	8
Charge-flip background	0	0.04	0	2.2
Luminosity	1.9	1.6	1.9	1.4
Pile-up estimate	1.1	0.6	0.6	1.6
Trigger efficiency	0.1	0.1	0.1	0.01
Normalization factor	3.8	8	6.0	13
Statistical	1.2	3.2	2.7	5.1

WVγ: Event Selections

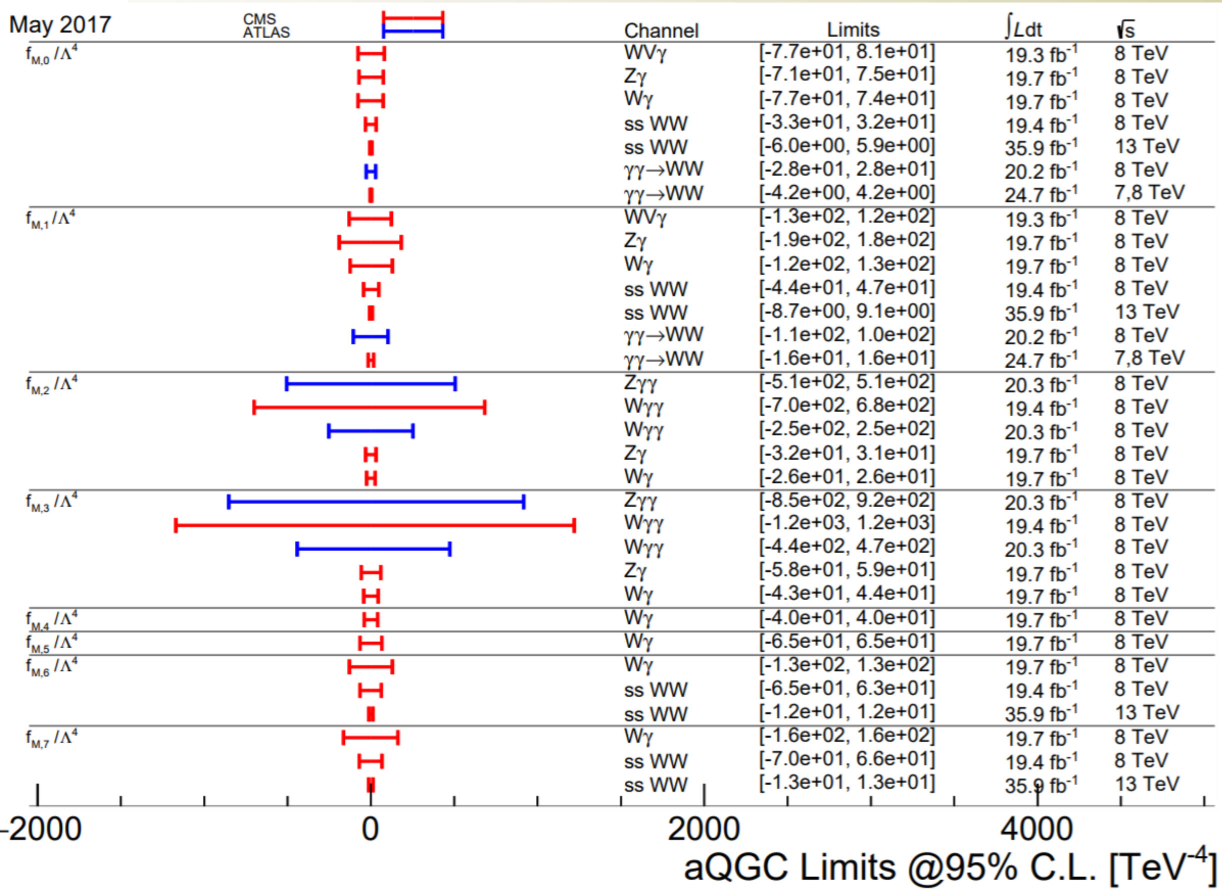
	$e\nu\mu\nu\gamma$	$\ell\nu jj\gamma$
Leptons	1 electron and 1 muon $p_T > 20$ GeV no 3rd lepton ($p_T > 7$ GeV) $\lvert\eta\rvert < 2.5$ opposite charge leptons $\Delta R(\ell, \ell) > 0.1$	1 electron or 1 muon $p_T > 25$ GeV no 2nd lepton ($p_T > 7$ GeV) $\lvert\eta\rvert < 2.5$
Photon	≥ 1 isolated photon $E_T > 15$ GeV isolation fraction $\epsilon_h^p < 0.5$ $\lvert\eta\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.5$	
Jets	$N_{jets} = 0$ $p_T > 25$ GeV $\lvert y\rvert < 4.4$ $\Delta R(\text{jet}, \gamma) > 0.5$ $\Delta R(\text{jet}, \ell) > 0.3$	$N_{jets} \geq 2$ and $N_{b\text{-jets}} = 0$ $p_T > 25$ GeV $\lvert\eta\rvert < 2.5$ $\lvert\Delta\eta_{jj}\rvert < 1.2$ $\Delta R_{jj} < 3.0$ $70\ \text{GeV} < m_{jj} < 100$ GeV $\Delta R(\text{jet}, \gamma) > 0.5$ $\Delta R(\text{jet}, \ell) > 0.3$
W boson	$E_{T,rel}^{miss} > 15$ GeV $m_{e\mu} > 50$ GeV	$E_T^{miss} > 30$ GeV $m_T > 30$ GeV

CMS limit

CMS-PAS-SMP-13-009

Observed Limits	Expected Limits
$-77\ (\text{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\text{TeV}^{-4})$	$-89\ (\text{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\text{TeV}^{-4})$
$-131\ (\text{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\text{TeV}^{-4})$	$-143\ (\text{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131\ (\text{TeV}^{-4})$
$-39\ (\text{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40\ (\text{TeV}^{-4})$	$-44\ (\text{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46\ (\text{TeV}^{-4})$
$-66\ (\text{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62\ (\text{TeV}^{-4})$	$-71\ (\text{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66\ (\text{TeV}^{-4})$

ATLAS/CMS limit



CMS EWK ss WW $\to \ell^{+/-}\ell^{+/-}$qq: using 19.4 fb^{-1} of 8 TeV pp collisions Phys. Rev. Lett. 114, 051801 (2015)

CMS $VW\gamma \to jj\ell\bar{\nu}\gamma$ triboson production with 19.3 fb^{-1} of 8 TeV pp collisions Phys. Rev. D 90, 032008 (2014)

CMS $\gamma\gamma \to W^+W^- \to e^+\mu^-$ scattering with 5.0 fb^{-1} of 7 TeV and 19.7 fb^{-1} of 8 TeV pp collisions Submitted to JHEP

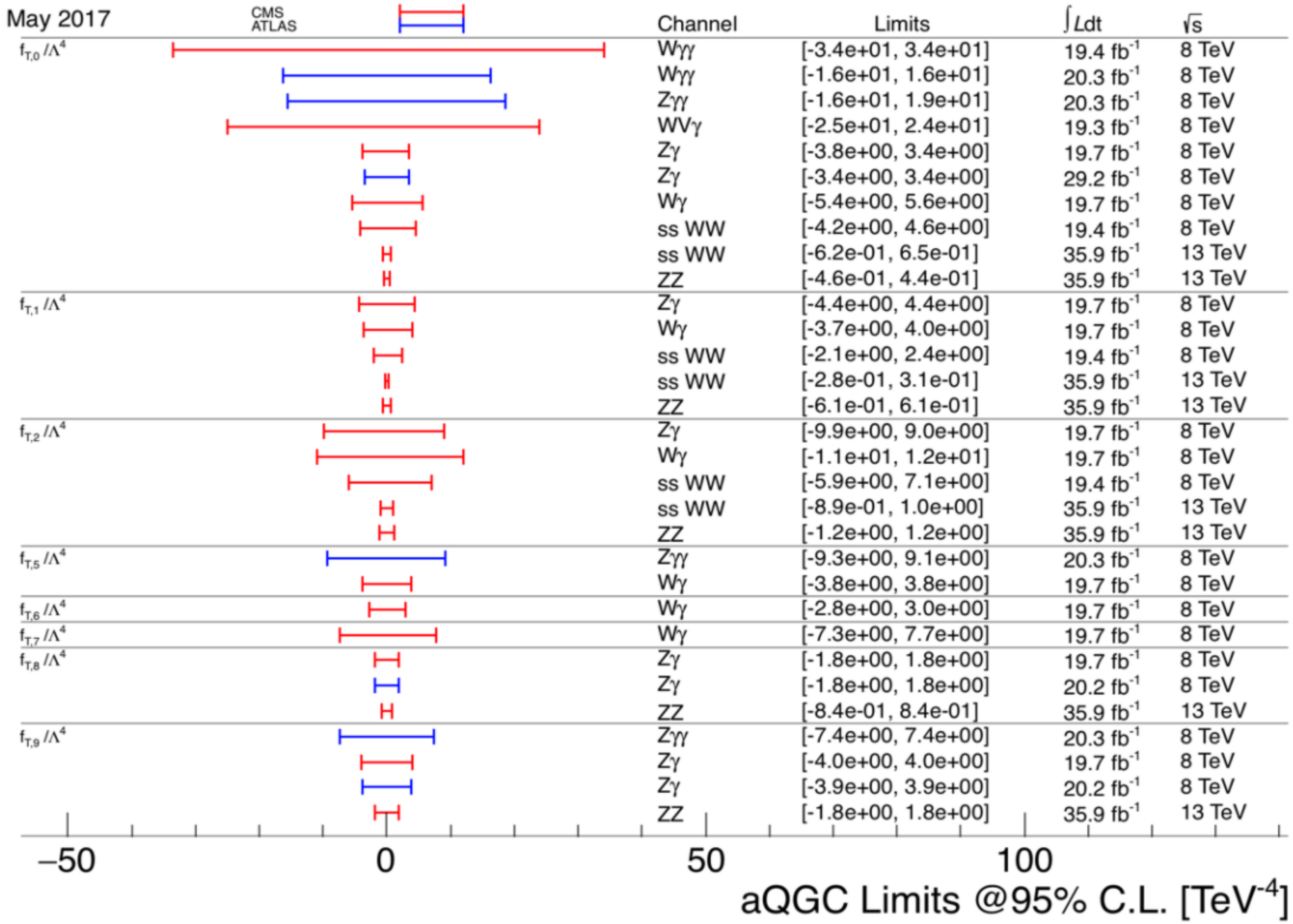
CMS EWK qq $\to Z\gamma qq \to \ell^+\ell^-\gamma$qq: using 19.7 fb^{-1} of 8 TeV pp collisions CMS-PAS-SMP-14-018

CMS EWK qq $\to W\gamma qq \to \ell^+\nu\gamma$qq: using 19.7 fb^{-1} of 8 TeV pp collisions CMS-PAS-SMP-14-011

CMS $W\gamma\gamma \to \ell\bar{\nu}\gamma\gamma$ and $Z\gamma\gamma \to \ell^+\ell^-\gamma\gamma$triboson production with 19.4 fb^{-1} of 8 TeV pp collisions Submitted to JHEP

ATLAS $W\gamma\gamma \to \ell\bar{\nu}\gamma\gamma$ triboson production with 19.3 fb^{-1} of 8 TeV pp collisions Phys.Rev.Lett. 115 (2015) 3, 031802

ATLAS/CMS limit



CMS EWK ss WW $\to \ell^{+/-}\ell^{+/-}$qq: using 19.4 fb^{-1} of 8 TeV pp collisions Phys. Rev. Lett. 114, 051801 (2015)

CMS $VW\gamma \to jj\ell\bar{\nu}\gamma$ triboson production with 19.3 fb^{-1} of 8 TeV pp collisions Phys. Rev. D 90, 032008 (2014)

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