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

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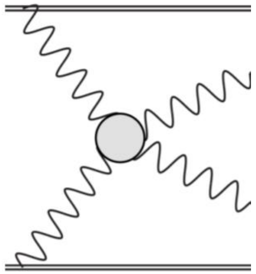
Outline

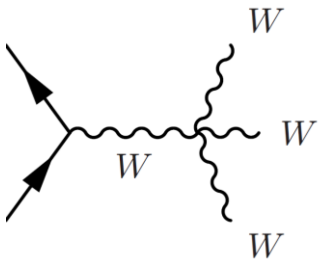
- Physics motivation
- VBS final states
  - Covered in Bo Liu's talk
- Tri-boson final states
  - WWW
  - WVγ (V = W, Z)
- Summary

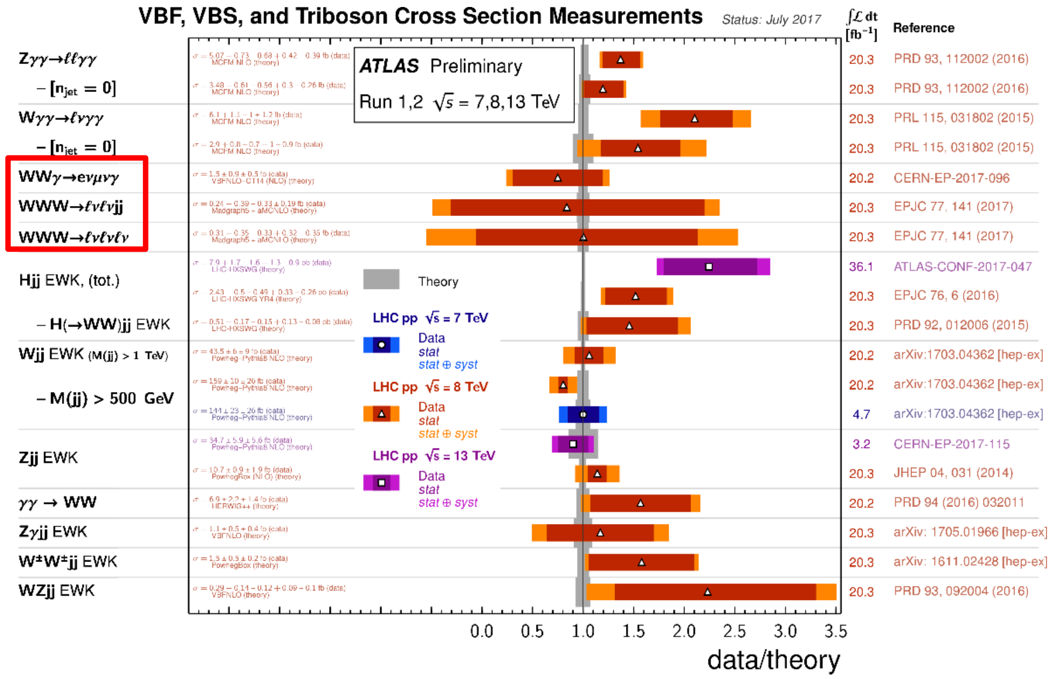
- Results with 20.2 fb^{-1}, 8 TeV dataset

Physics Motivation

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

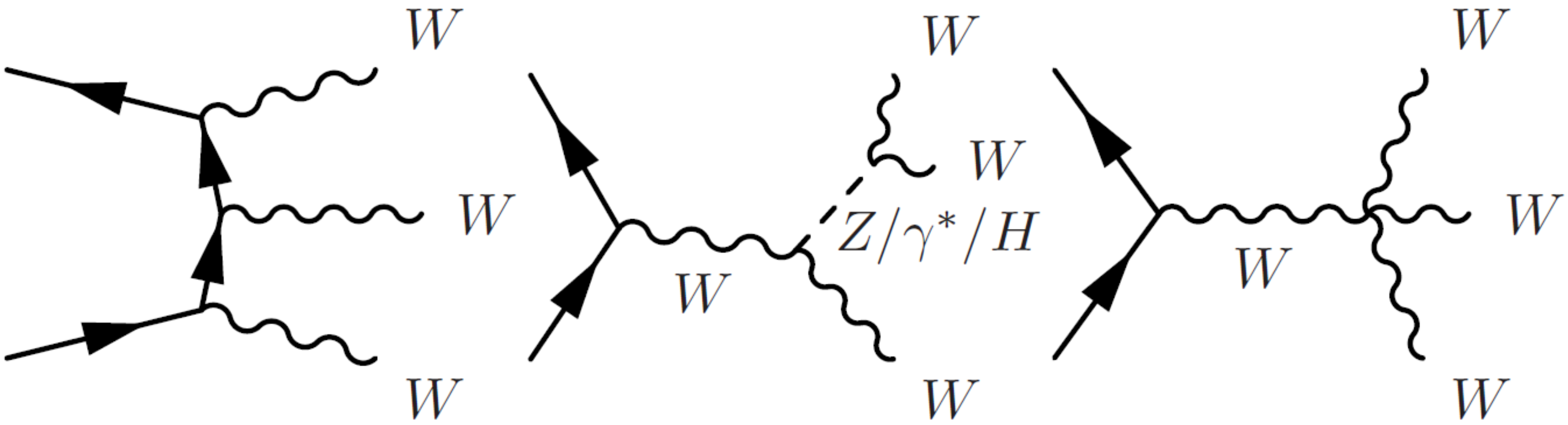






Triboson: WWW

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



LO processes

Dominant background from WZ/γ* + jets process

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WWW: Event Selections

lvlvlv: split based on number of same-flavor, opposite-sign lepton (SFOS) pairs

0 SFOS	1 SFOS	2 SFOS
Exactly three charged leptons with $p_T > 20$ GeV		
$\lvert \Phi^{3l} - \Phi p_T^{miss} \rvert > 2.5$		
Z boson veto (different mass window depending on channels)		
Jet veto and b-jet veto		
$m_{ll} > 20$ GeV	$E_T^{miss} > 45$ GeV	$E_T^{miss} > 55$ GeV

lvlvjj: split based on lepton flavor

$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Exactly two same-charge leptons with $p_T > 30$ GeV		
At least two jets with $p_T > 30/20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{ll} > 40$ GeV, $65 < mjj < 105$ GeV and $\lvert d\eta(jj)\rvert < 1.5$		
$E_T^{miss} > 55$ GeV		
Z boson veto		
No third lepton and no b-jets		

Same-sign channel has much better Drell-Yan suppression

WWW: Background Estimation

- Background with prompt leptons estimated using simulated events
  - WZ/γ* + jets, diboson, other triboson, $t\bar{t}V$
- Charge-flip background (occurs primarily from hard bremsstrahlung photon conversion)
  - Charge-flip rate estimated using Z→ee events
- Fake background
  - lvlvlv: estimated with tag-and-probe method
    - “Tag” lepton to identify the event
    - “Probe” lepton to study the probabilities of prompt or non-prompt leptons to satisfy the signal lepton selections
  - lvlvjj: fake factors calculated with events containing one signal lepton and one “lepton-like” jet

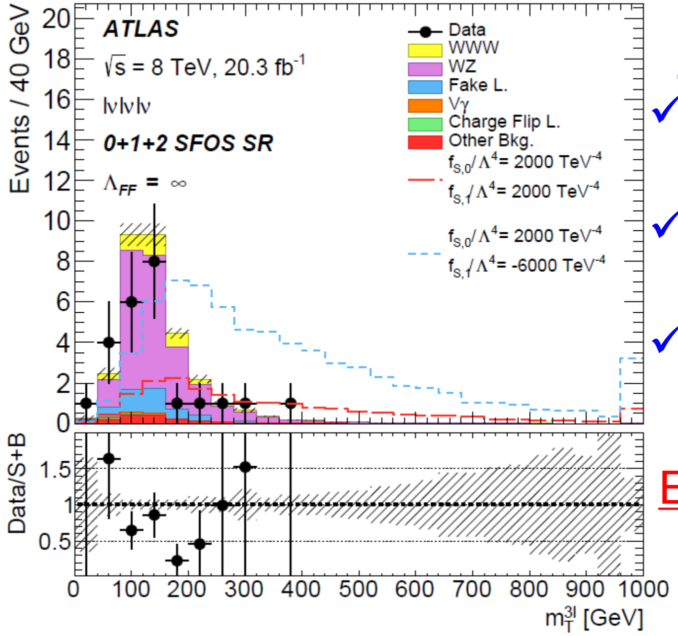
WWW: Systematics

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

Dominant systematics from jet energy scale and resolution, and fake-lepton background

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 (Λ_{FF} = ∞) shown here as example
- ✓ Two different sets of $f_{S,0}/\Lambda^4$ and $f_{S,1}/\Lambda^4$ configurations

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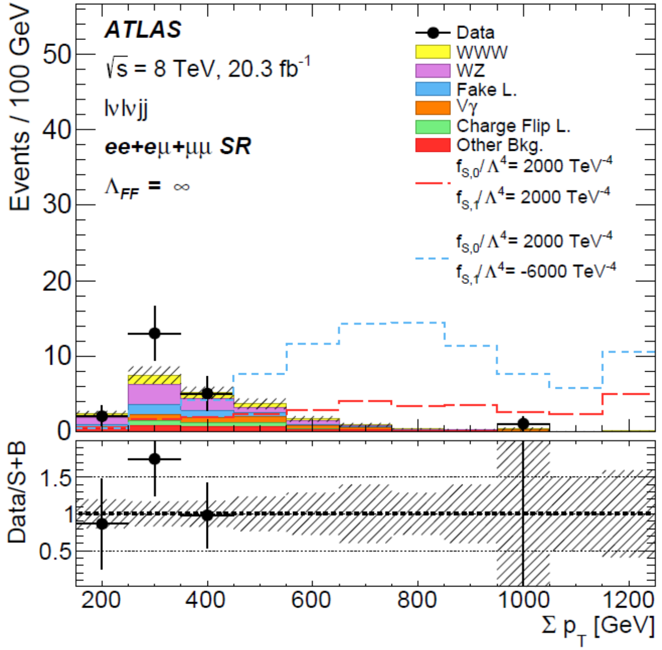
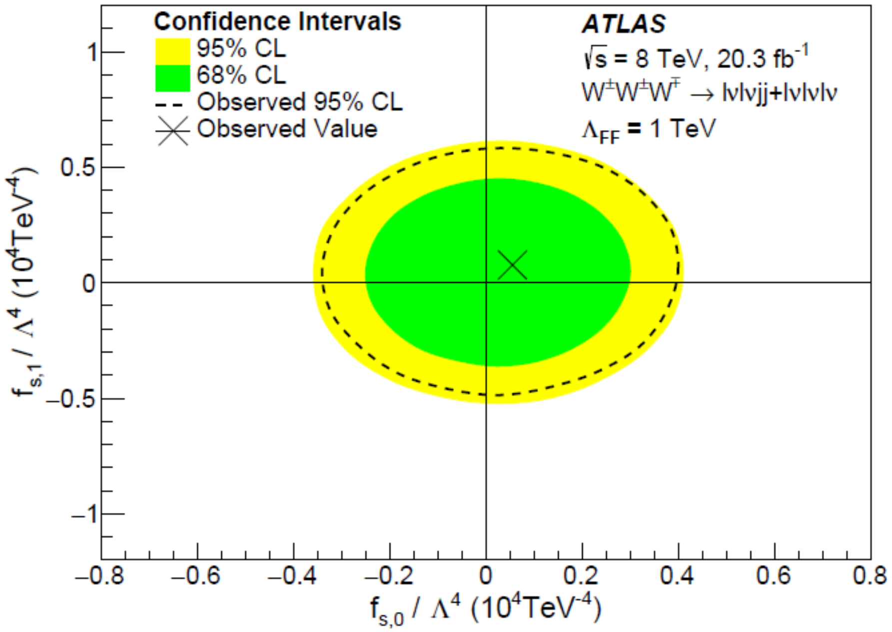
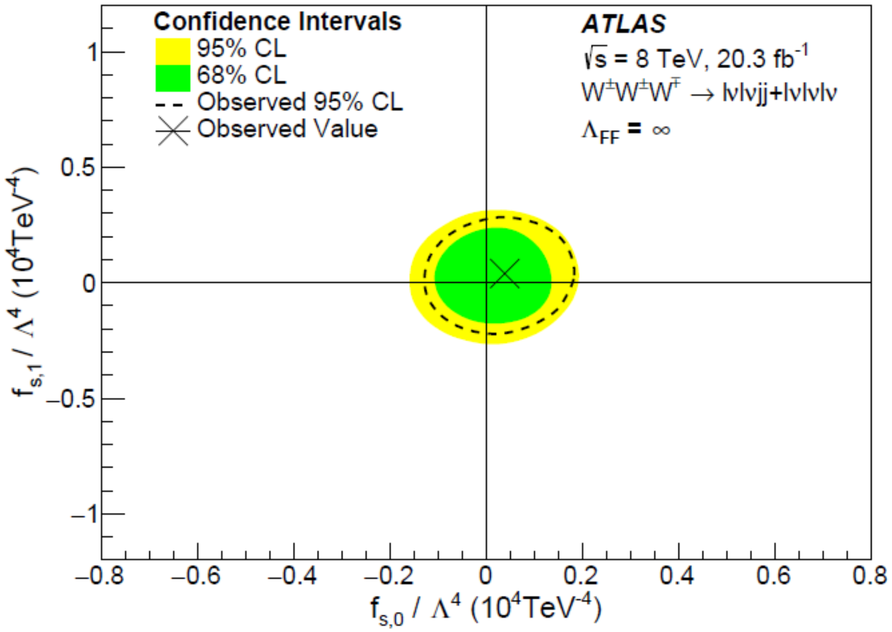


	Cross section (fb)	
	Theory	Observed
Fiducial		
$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (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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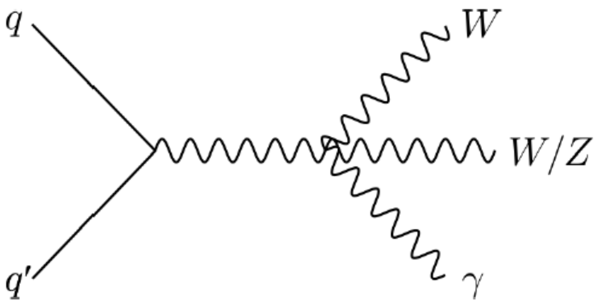
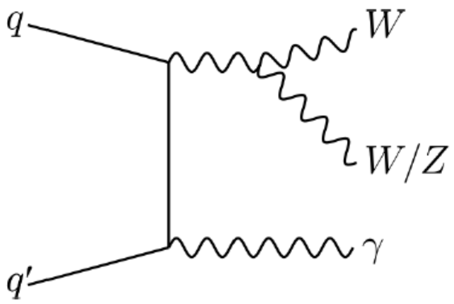
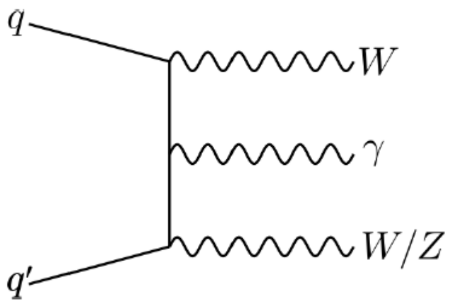
Triboson: WVγ (V = W, Z)







Produced through QGC

Produced through radiation

Fully leptonic channel (WWγ only) and semi-leptonic channel

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

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Wνγ: Event Selections

$e\nu\mu\nu\gamma$	$l\nu jj\gamma$
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

Fully leptonic channel
- ✓ Only eμ channel
- ✓ Same-flavor channels are not included as they have large background

Semileptonic channels
- ✓ Profits from larger hadronic branching ratio of W/Z decays
- ✓ τ channel not included

WVγ: Background Estimation

eνμνγ: signal region

Process	Events
$t\bar{t}\gamma$	4.1 ± 1.9
$Z\gamma$	2.7 ± 1.2
$WZ\gamma$	2.7 ± 0.6
Fake γ from e	2.3 ± 0.6
Fake γ from jets	$1.7\,^{+3.3}_{-1.4}$
$WW\gamma$ (τ contribution)	1.0 ± 0.1
Wt	0.3 ± 0.1
ZZ	0.2 ± 0.1
Fake μ from jets	0.1 ± 0.1
Fake e from jets	$0.0\,^{+0.6}_{-0.0}$
Total background	15.1 ± 4.1
Expected signal	12.2 ± 1.1
Data	26

Semileptonic channel: signal region

Process	Electron Channel	Muon Channel
$W\gamma$ + jets	324 ± 11	407 ± 11
Fake γ from jets	82 ± 7	117 ± 9
Fake ℓ from jets	57 ± 6	27 ± 5
$t\bar{t}\gamma$	35 ± 6	46 ± 7
Fake γ from e	33 ± 12	3 ± 1
$Z\gamma$ + jets	19 ± 4	20 ± 3
$WV\gamma$ (τ contribution)	< 1	< 1
Total background	552 ± 38	621 ± 31
Expected signal	14 ± 2	18 ± 2
Data	490	599

Estimated with 2D sideband method

Others directly from simulation, or with simultaneous fit

Wγ: Cross-section Measurements

- ✓ Fiducial cross section measured in fully leptonic channel
  - ✓ Expected significance: 1.6σ
  - ✓ Observed significance: 1.4σ
  - ✓ QCD NLO cross section predicted by VBFNLO

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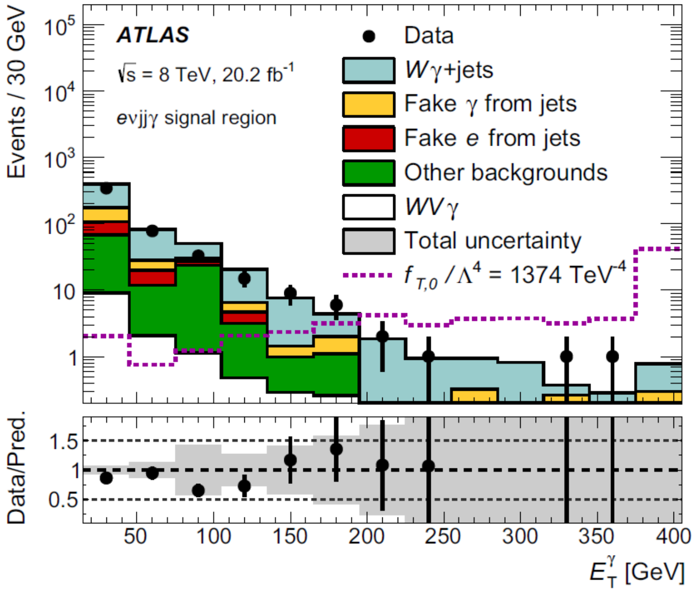
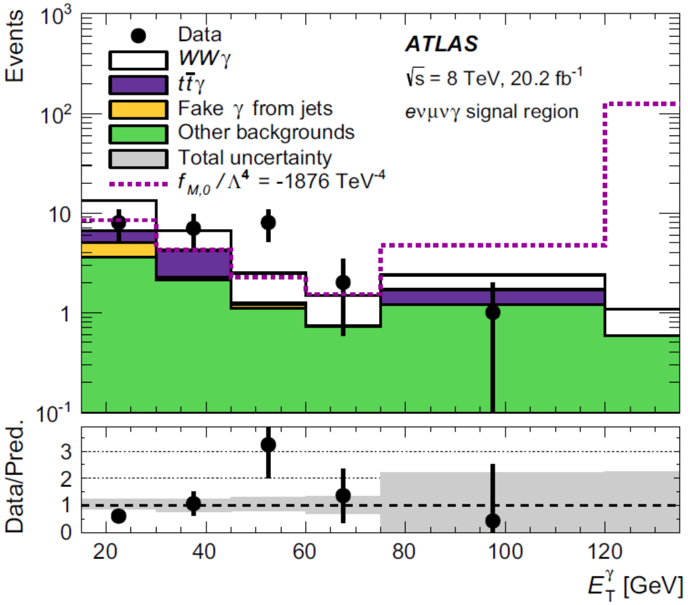
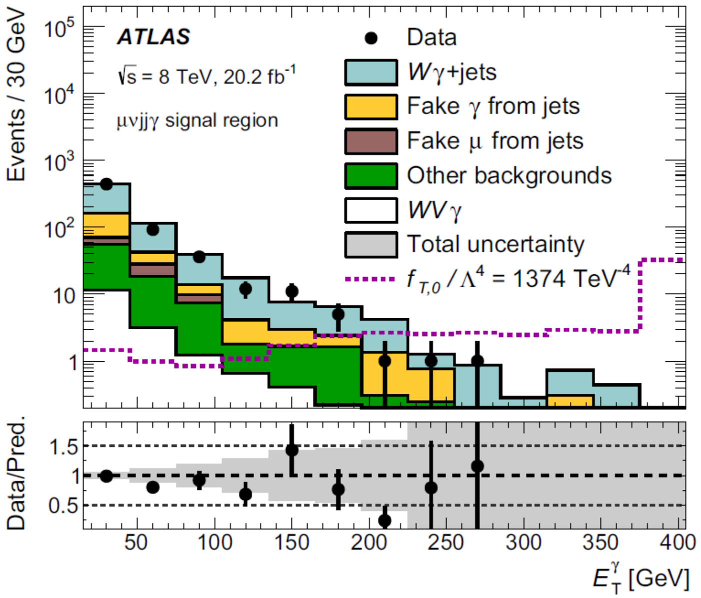
$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = (1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.}))\ \text{fb}$$



		Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0 ± 0.1
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4 ± 0.1
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2 ± 0.1
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3 ± 0.1

Prediction from VBFNLO at particle level

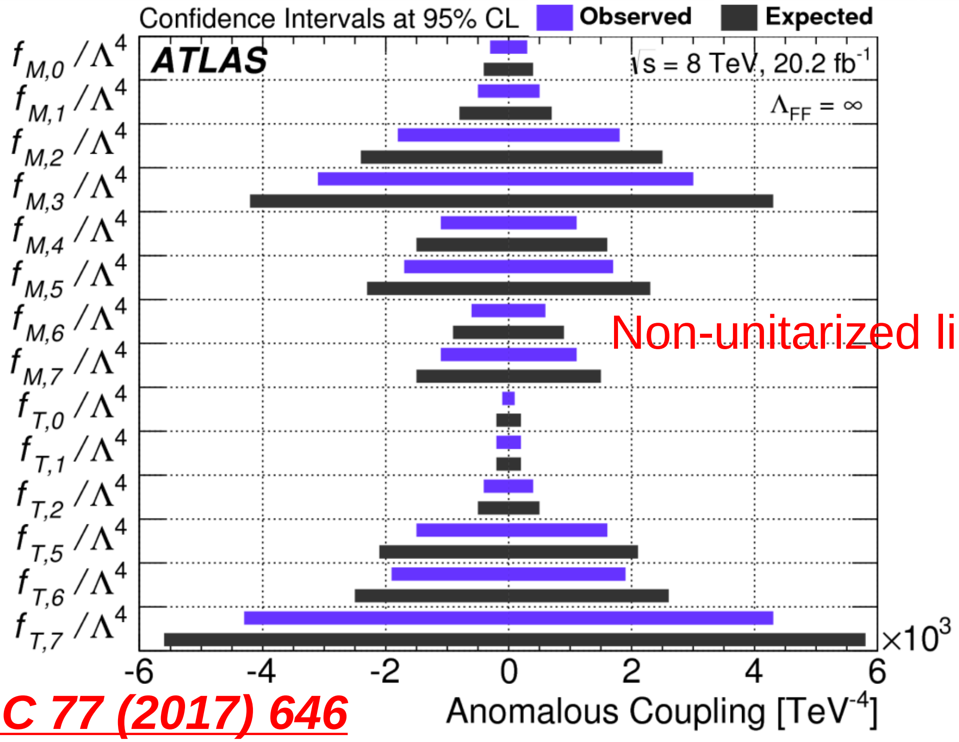




WVγ: aQGCs

- 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)

Upper limits		E_T^γ threshold [GeV]	Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	120	0.3	$0.3^{+0.3}_{-0.1}$	0.076 ± 0.004
Semileptonic	$e\nu jj\gamma$	200	1.3	$1.3^{+0.5}_{-0.3}$	0.057 ± 0.013
Semileptonic	$\mu\nu jj\gamma$	200	1.1	$1.1^{+0.5}_{-0.3}$	0.051 ± 0.011
Semileptonic	$\ell\nu jj\gamma$	200	0.9	$0.9^{+0.3}_{-0.2}$	0.054 ± 0.009



Non-unitarized limits

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Summary

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

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

backup

aQGC

- Effective operators approach

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

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

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	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

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

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 $p_{\mathrm{T}} > 20$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	$E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	–	
Angle between trilepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$		$\lvert\phi^{3\ell} - \phi^{\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}\rvert > 2.5$	
Z boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$m_Z - m_{\mathrm{SFOS}} > 35$ GeV or $m_{\mathrm{SFOS}} - m_Z > 20$ GeV	$\lvert m_{\mathrm{SFOS}} - m_Z\rvert > 20$ GeV
Jet veto	At most one jet with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 4.5$		
b-jet veto	No identified b−jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

Split based on lepton flavor

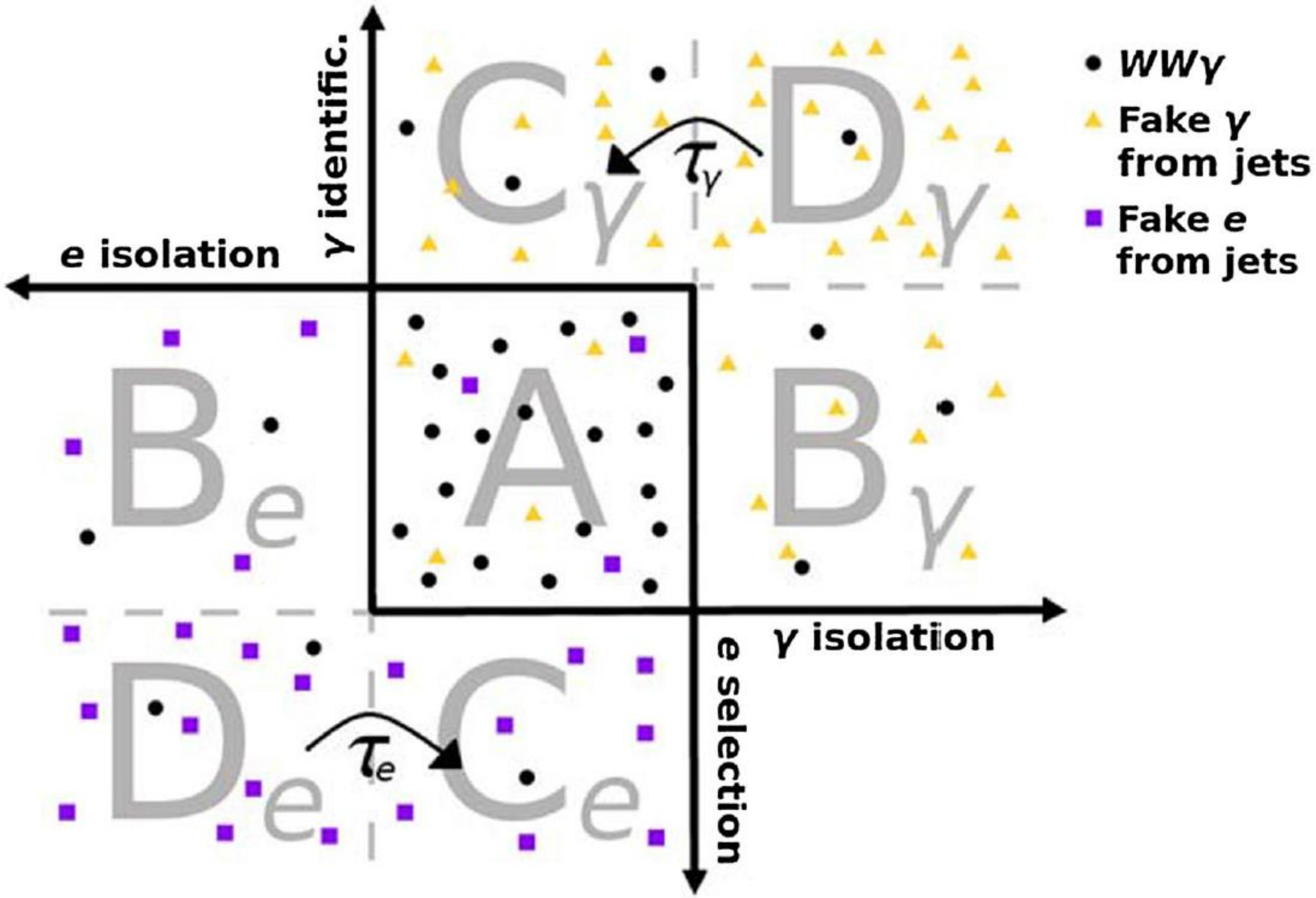
$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Lepton	Exactly two same-charge leptons with $p_{\mathrm{T}} > 30$ GeV		
Jets	At least two jets with $p_{\mathrm{T}}(1) > 30$ GeV, $p_{\mathrm{T}}(2) > 20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ 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 $p_{\mathrm{T}} > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified b-jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

Same-sign channel has much better Drell-Yan suppression

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	$N_{\text{jets}} = 0$ $p_T > 25$ GeV $\lvert y\rvert < 4.4$ $\Delta R(\text{jet}, \gamma) > 0.5$ $\Delta R(\text{jet}, \ell) > 0.3$	$N_{\text{jets}} \geq 2$ 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 GeV $< m_{jj} <$ 100 GeV $\Delta R(\text{jet}, \gamma) > 0.5$ $\Delta R(\text{jet}, \ell) > 0.3$
W boson	$E_{\text{T, rel}}^{\text{miss}} > 15$ GeV $m_{e\mu} > 50$ GeV	$E_T^{\text{miss}} > 30$ GeV $m_T > 30$ GeV

WVγ: 2D sideband method

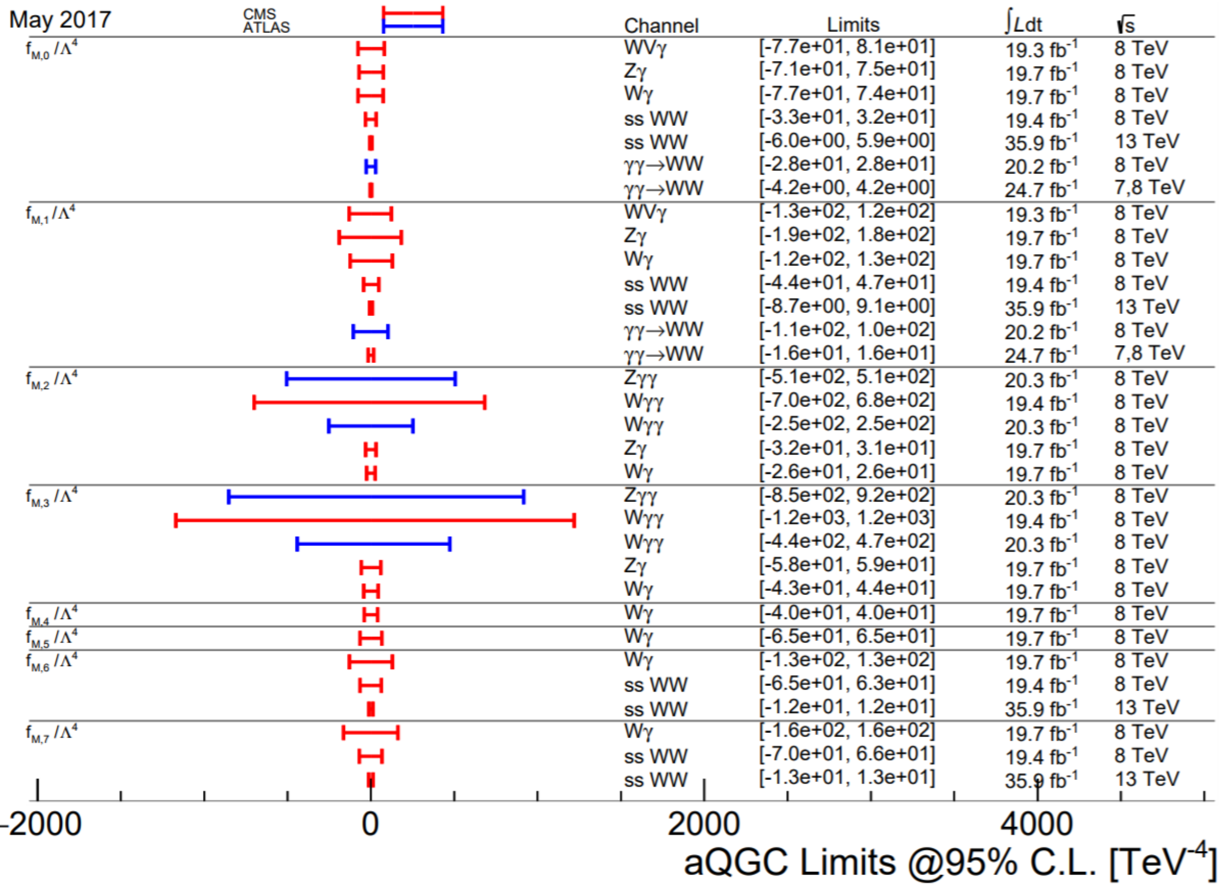


CMS limit

CMS-PAS-SMP-13-009

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

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

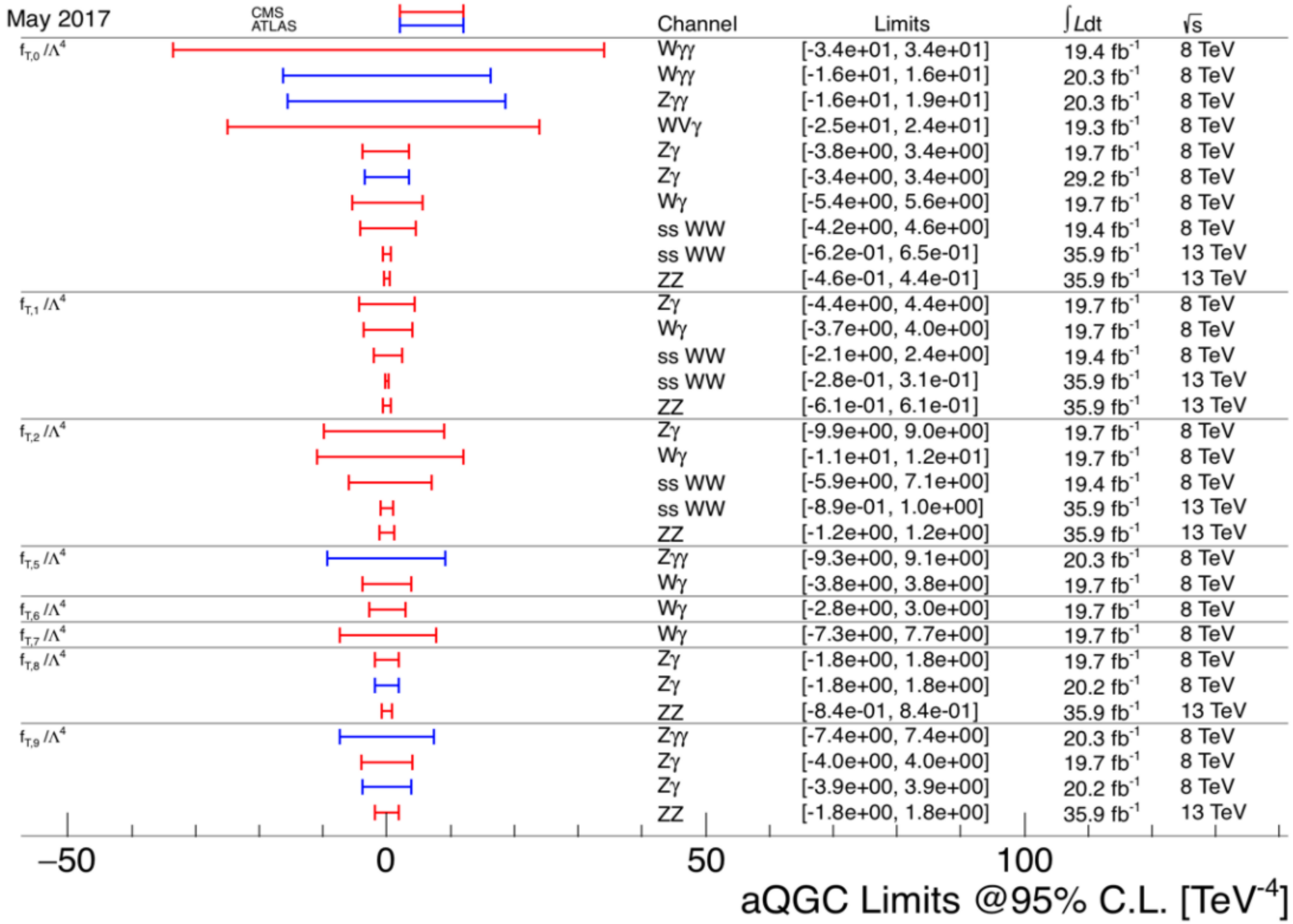
CMS EWK qq $\to Z\gamma qq \to \ell^+\ell^-\gamma$qq: using 19.7 fb^{-1} of 8 TeV pp collisions CMS-PAS-SMP-14-018

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



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