Measurements of Diboson Production and Vector Boson Scattering

Hal Evans, Indiana University
for the ATLAS & CMS Collaborations

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Outline

Diboson Physics

- Cross-Sections & Anomalous couplings

Experimental Considerations

- Datasets, Triggers, Objects, Backgrounds

Measurements

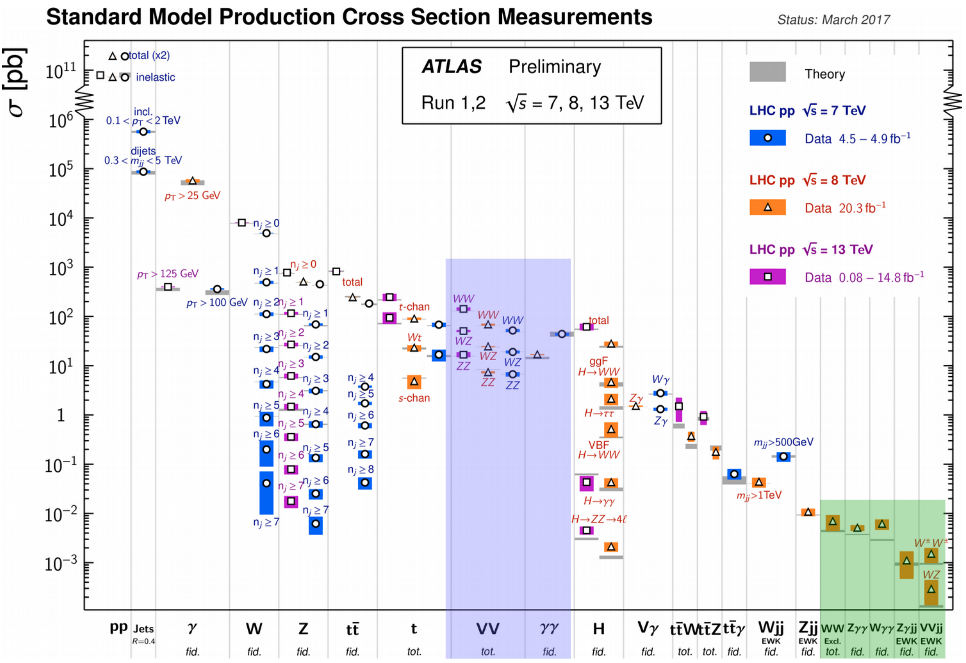
- Cross-Section measurements & comparison to theory
- Anomalous Triple & Quartic Gauge Couplings
- Summaries (>50 ATLAS & CMS publications in this area !)
  - Few more details on recent results (14 in last 6 months !)

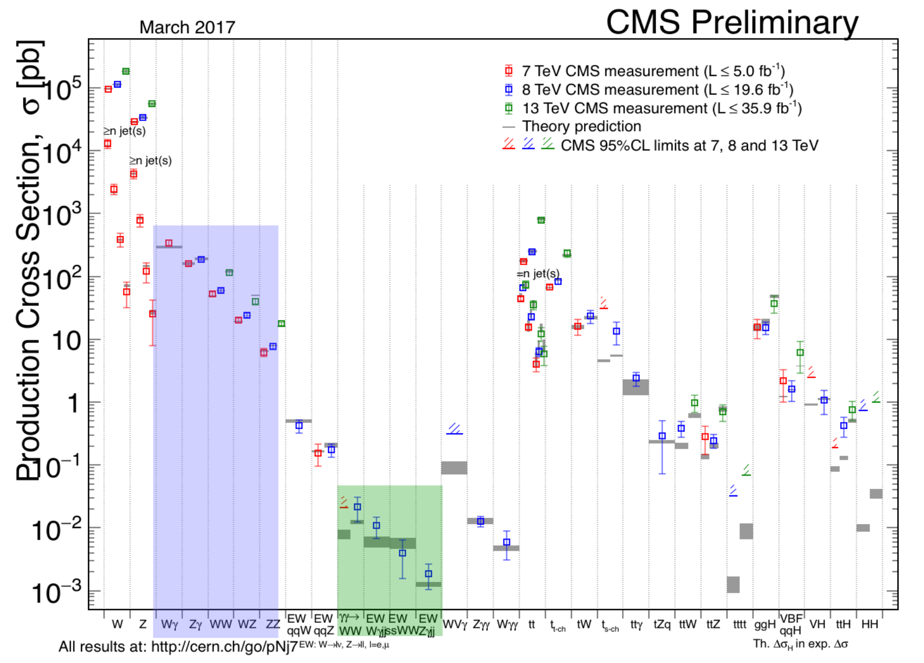
Future Prospects

- Upgrades & projected sensitivity

Diboson Physics

Diboson Production and the SM





Total Cross-Section dominated by QCD effects

- Test higher order QCD calculations: (N)NLO

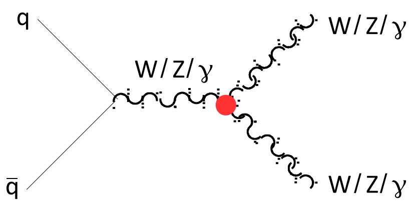
EWK production enhanced in certain regions

- Test higher order QED, nature of EWSB, gauge structure of the SM and beyond

Vector Boson Scattering

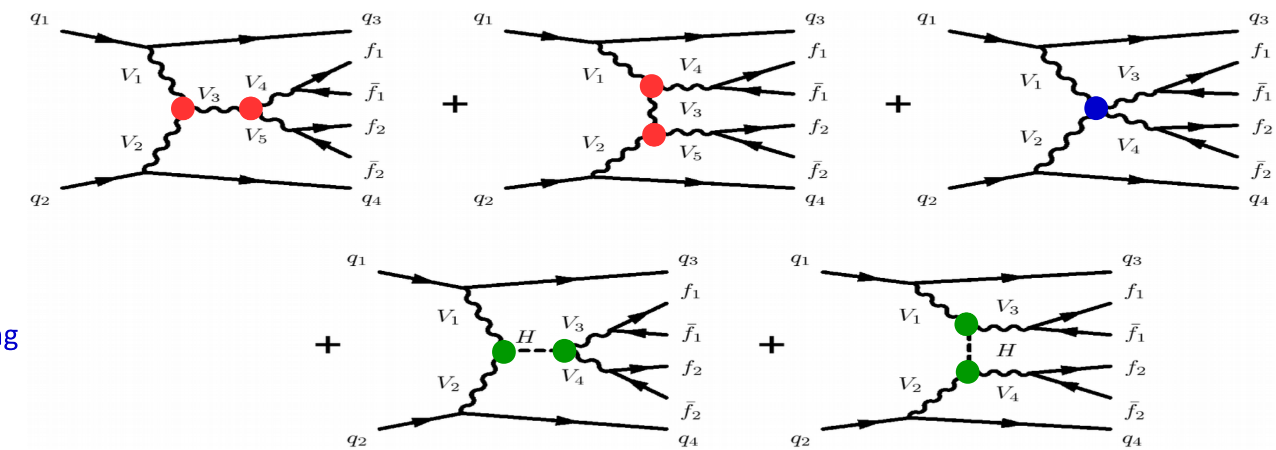
Vector Boson Couplings

Lowest Order

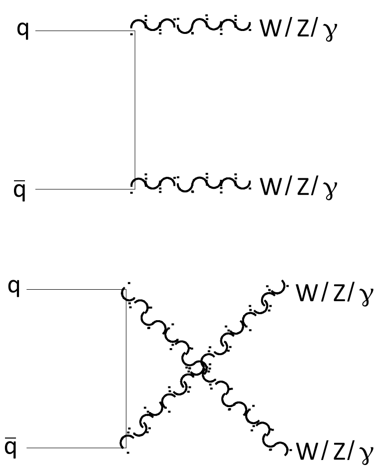


- Triple Gauge Coupling
- Quartic Gauge Coupling
- Higgs Coupling

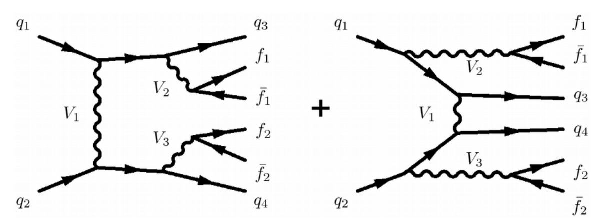
Higher Order (V V j j)



Non-VBS Diboson

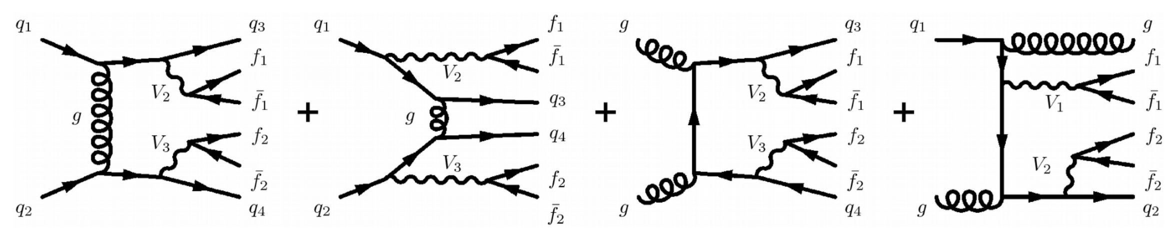


EWK



Interference

QCD



Anomalous Couplings

Only certain multi-gauge-boson couplings are non-zero in the SM

- Tree-Level TGCs: WWZ, WWγ
- Tree-Level QGCs: WWWW, WWγγ, WWZZ, WWZγ
- Beyond SM physics can modify these couplings or lead to new ones

Anomalous couplings are probed using Effective Field Theory

- Dimension 6 Operators ==> Triple Gauge Couplings
- Dimension 8 Operators ==> Quartic Gauge Couplings

D = 6 D = 8

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

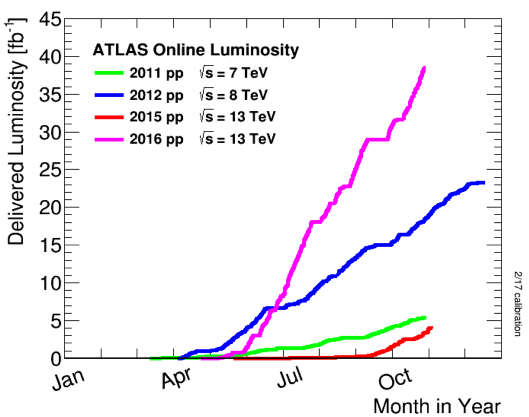
Only $D_\mu\phi$ Only Field Strength $D_\mu\phi$ + Field Strength

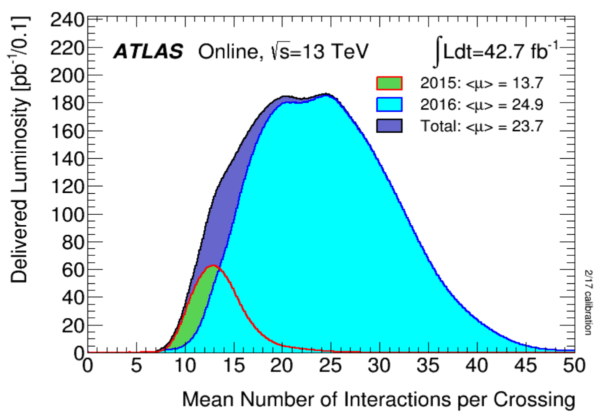
- EFT only valid to New Physics Scale (Λ)
  - Can use Form Factors to model cut-off: $f \rightarrow f\left(1+\frac{s}{\Lambda}\right)^{-p}$

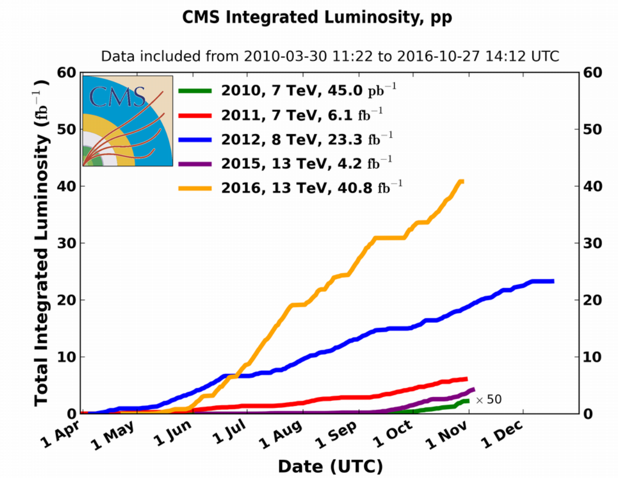
Experimental Considerations

Data Sets

pp Data Taking			ATLAS (fb^{-1})		CMS (fb^{-1})	
Year	√s	BC	Delivered	Recorded	Delivered	Recorded
2010	7 TeV	50 ns	0.048	0.045	0.045	0.041
2011	7 TeV	50 ns	5.5	5.1	6.1	5.6
2012	8 TeV	50 ns	22.8	21.3	23.3	21.8
2015	13 TeV	25 ns	4.2	3.9	4.2	3.8
2016	13 TeV	25 ns	38.5	35.6	40.8	37.8







Diboson Building Blocks

Representative threshold cuts on objects used in diboson analyses

Photons

- E_T > 15-25 GeV

Leptons (W → eν,μν ; Z → ee,μμ)

- Electrons: p_T > 25 GeV (lower for dileptons, e.g. > 17/12 GeV - CMS)
- Muons: p_T > 25 GeV (lower for dileptons, e.g. > 17/8 GeV - CMS)
- Taus: generally not reconstructed for these analyses

Jets (W/Z → qq ; other jets in the event)

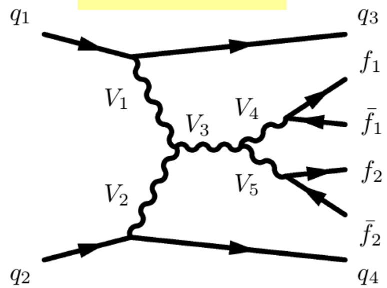
- Forward: E_T > 30 GeV
- Resolved (V → jj): E_T > 25 GeV
- Merged (V → J): E_T > 200 GeV

Missing Energy (Neutrinos)

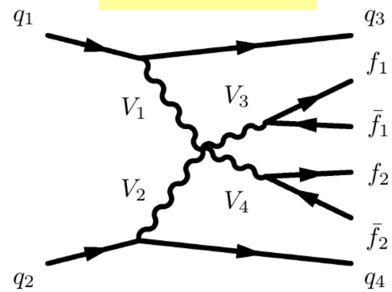
- E_T^{miss} > 40-100 GeV

Accessing TGCs & QGCs

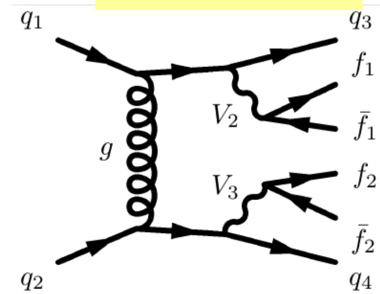
EWK: TGC



EWK: QGC



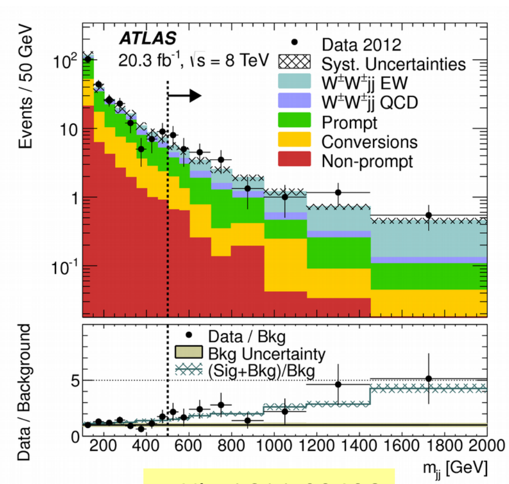
QCD Diboson



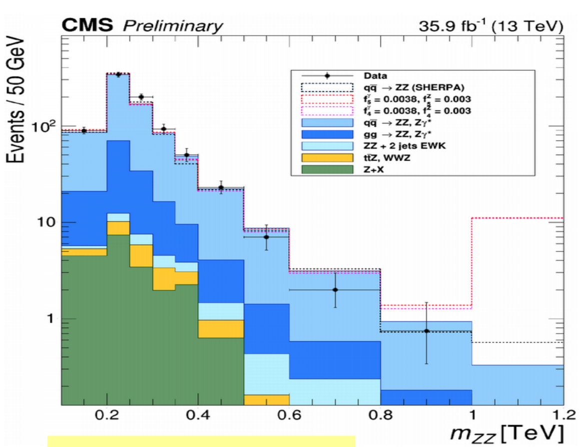
Distinguishing characteristics of events with multi-boson vertices

- Forward jets: high m_{jj} & Δy_{jj}, no color connect.

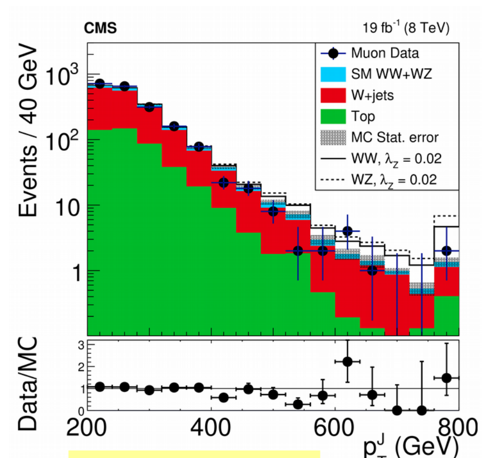
Anomalous Couplings: enhanced at high m(VV), p_T(V) ...



arXiv:1611.02428



CMS-PAS-SMP-16-017



arXiv:1703.06095

Triggering

Primary triggers used for Diboson analyses: Single Leptons (e/μ)

- γγ results use diphoton triggers w/ E_T thresholds: ~35/25 GeV
- Dilepton (ee,μμ,eμ) also used in some analyses
  - ee: 12/12 GeV, μμ: 17-18/8 GeV

Representative Single-Lepton Trigger Thresholds

- Note the use of increased thresholds & tighter isolation at higher luminosities

	Peak Lumi	ATLAS		CMS	
Year (√s)	(x 10^{33} $cm^{-2}s^{-1}$)	e-Threshold	μ-Threshold	e-Threshold	μ-Threshold
2011 (7 TeV)	3.7	22 GeV	18 GeV	Dilepton 17/8 GeV	
2012 (8 TeV)	7.7	24 GeV (Iso) 60 GeV (no Iso)	24 GeV (Iso) 50 GeV (no Iso)	24 GeV (Iso)	27 GeV (Iso)
2015 (13 TeV)	5.0	24 GeV (Iso) 60 GeV (no Iso)	24 GeV (Iso) 50 GeV (no Iso)	27 GeV (Iso)	27 GeV (Iso) 50 GeV (no Iso)
2016 (13 TeV)	13.8	26 GeV (Iso) 60 GeV (no Iso)	26 GeV (Iso) 50 GeV (no Iso)	27 GeV (Iso)	

Backgrounds & Systematics

Recent results give good overview of main diboson issues

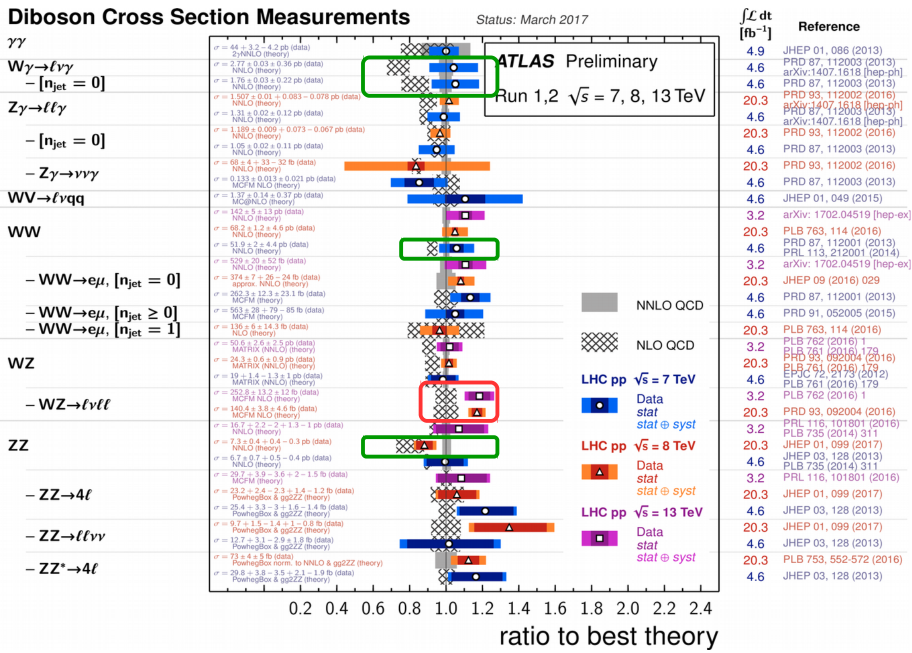
- All major backgrounds are estimated using data-based methods
  - Usually employing background-enhanced Control Regions

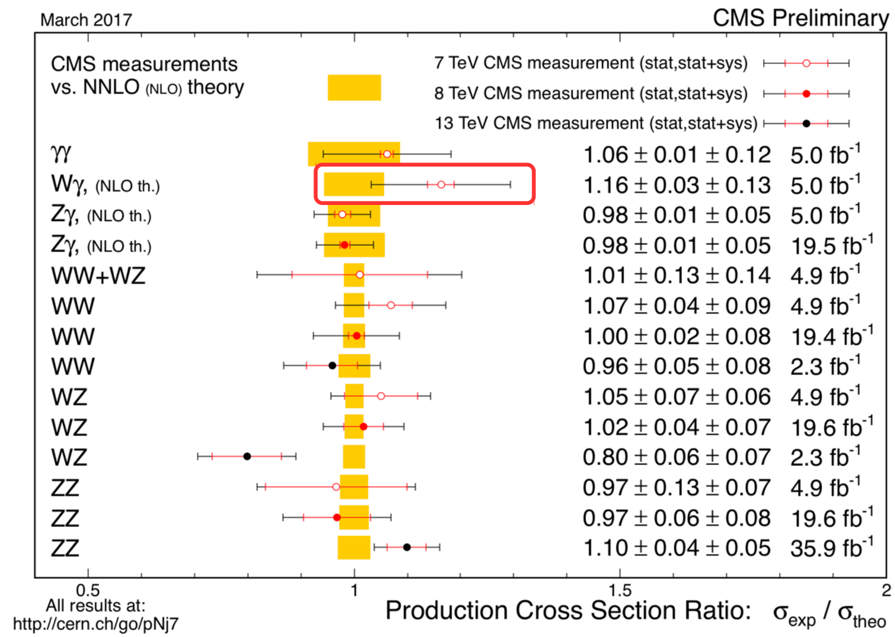
Exp	$\sqrt{s}$ (TeV)	Channel	Reference	Main Bgrds	Main Systs
ATLAS new	8	γγ	arXiv:1704.03839	Fake γ (j→π^0/η)	Photon ID efficiency
CMS new	13	ZZ+jets			
CMS new	13	ZZ → 4ℓ	CMS-PAS-SMP-16-017	Z+jets, WZ+jets	ℓ efficiency, trigger eff
ATLAS new	7,8	Wjj	arXiv:1703.04362	tt + Wt, multijet	Jet related
ATLAS	13	WW → eνμν	arXiv: 1702.04519	tt + Wt	Jet related
ATLAS	13	WZ → ℓ'νℓℓ	ATLAS-CONF-2016-043	Mis-ID leptons	Mis-ID ℓ bgrd, trigger eff
CMS new	13	WW/WZ → ℓνqq	CMS-PAS-SMP-16-012	W+jets	W+jets, V-tag
CMS new	8	WW/WZ → ℓνqq	arXiv:1703.06095	W+jets	W+jets
ATLAS new	8	WW/WZ → ℓνqq	STDM-2015-23	W+jets	Jet related
CMS	8	Wγjj	arXiv:1612.09256	QCD Wγ+jets, W+jets	W+jets, mis-ID j→e
CMS	8	Zγjj	arXiv:1702.03025	QCD Zγ+jets, Z+jets	QCD norm, Fake photon
ATLAS new	8	Zγjj	STDM-2015-21	QCD Zγ+jets, Z+jets	Jet related
ATLAS	8	$W^{\pm}$(ℓν)$W^{\pm}$(ℓν)jj	arXiv:1611.02428	WZjj	Jet related
CMS new	13	Wγγ/Zγγ	arXiv:1704.00366	Jet/e → γ mis-id	Jet → γ mis-ID

new = final since Moriond

Cross-Section Measurements

Diboson Cross-Sections





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

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

~All recent measurements are systematics limited

Generally good agreement between experiment and theory

- NNLO QCD improves agreement substantially in some cases
  - > New NNLO calculations for WZ (arXiv:1604.08576) and Vγ (arXiv:1504.01330)
- But some features observed in some differential measurements

New Results: ATLAS γγ (8 TeV)

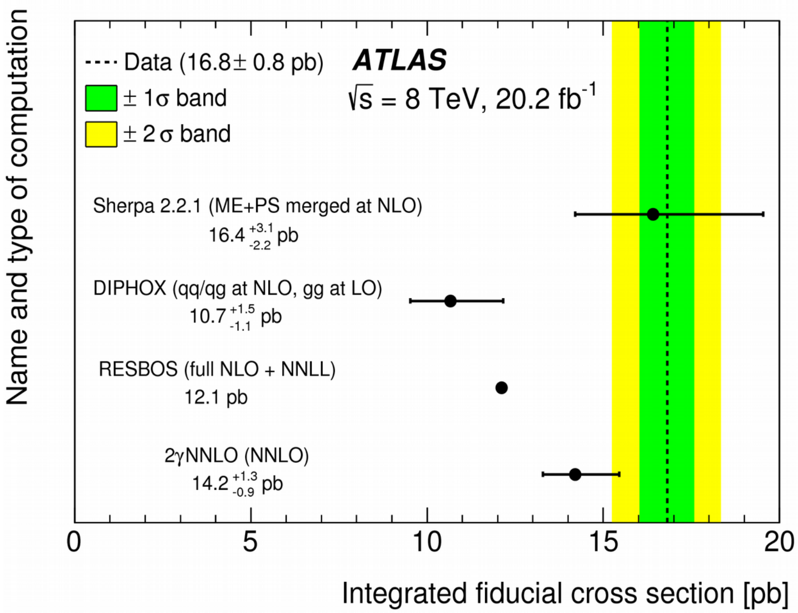
new

Total and Differential (vs. 6 variables) cross-sections

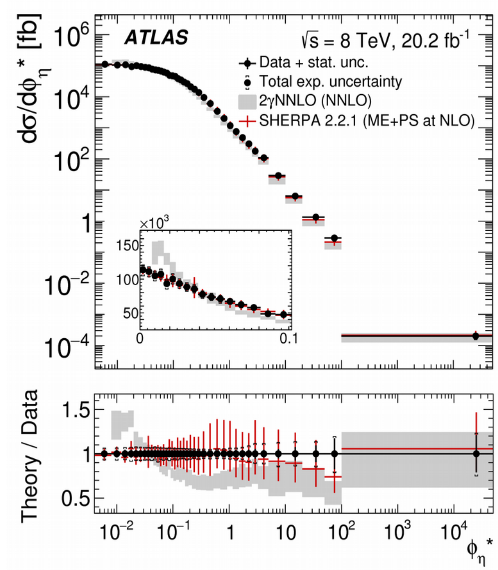
- Fixed order QCD predictions at NLO and NNLO do not reproduce data well
- Parton-level calc w/ varying jet-mult up to NLO matched to parton shower does a much better job

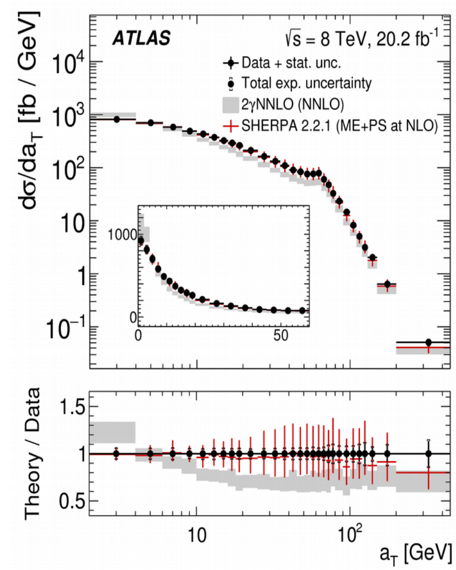
$$\phi^*_\eta = \tan\left(\frac{\pi-\Delta\phi_{\gamma\gamma}}{2}\right)\sin\theta^*_\eta$$

a_T = comp of $p_{T\gamma\gamma}$ transverse to thrust



Precision improved by ~factor of 2 wrt 7 TeV measurement
(JHEP 01, 086 (2013))





a_T & ϕ* probe infrared emmission effects

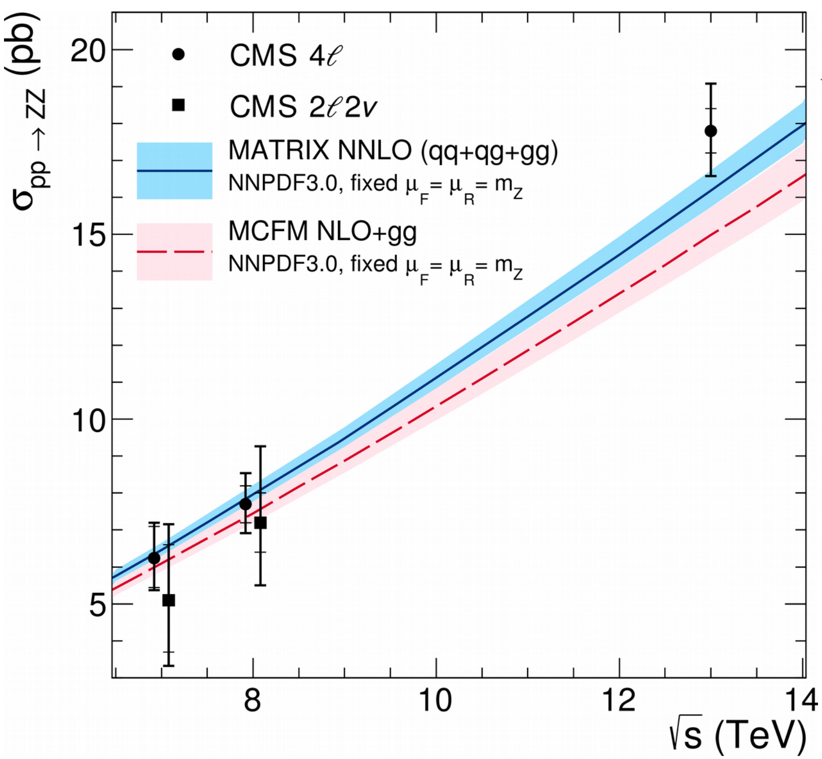
arXiv:1704.03839

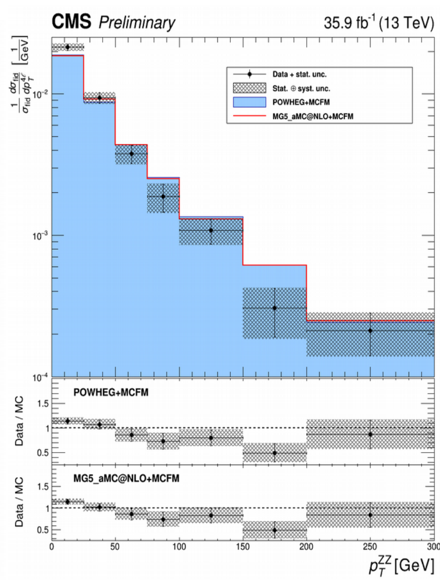
New Results: CMS ZZ (13 TeV)

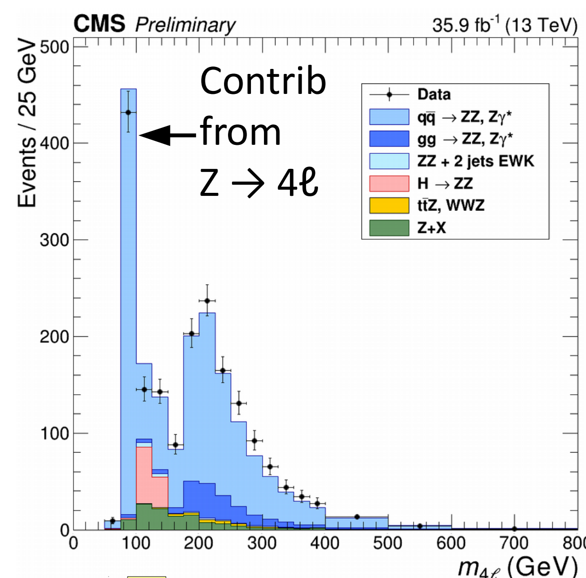
new

First diboson result with full 2015-16 dataset (35.9 fb^{-1})

- Good agreement of differential cross-sections with NNLO predictions



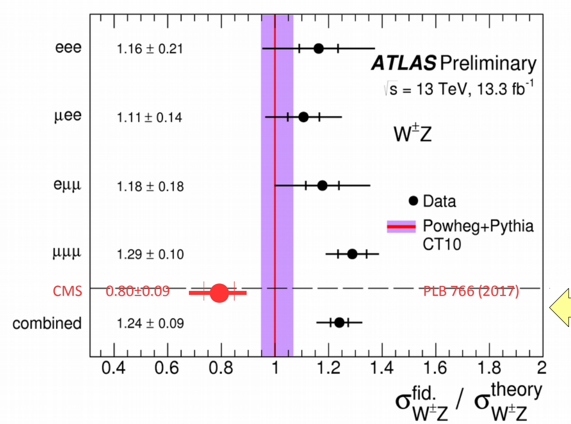




$$BR(Z \to 4l) = 4.74 \pm 0.16\,(\text{stat})^{+0.18}_{-0.17}\,(\text{syst}) \pm 0.08\,(\text{theo}) \pm 0.12\,(\text{lumi}) \times 10^{-6}$$

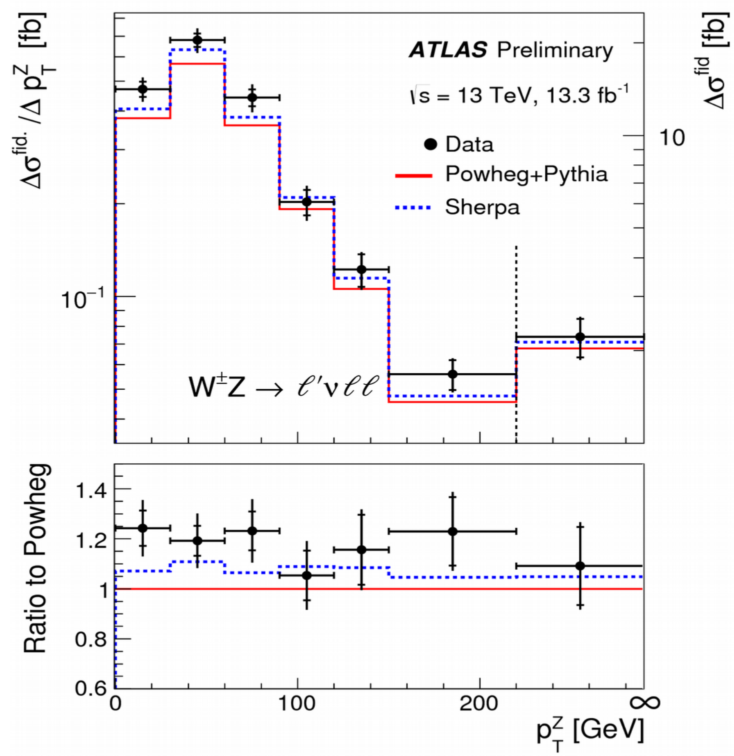
Recent Results: WW/WZ (13 TeV)

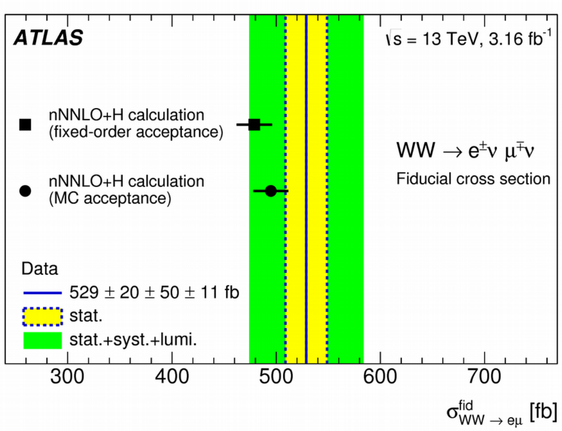
Leptonic W/Z decays: WZ → ℓ'νℓℓ , WW → eνμν



ATLAS-CONF-2016-043

Possible tension w/ CMS leptonic WZ measured at 13 TeV





new

Good agreement w/pred's (also in 13 TeV / 8 TeV ratio)

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

Good agreement w/ nNNLO+H predictions

arXiv:1702.04519

Gauge Coupling Measurements

Neutral aTGCs

new

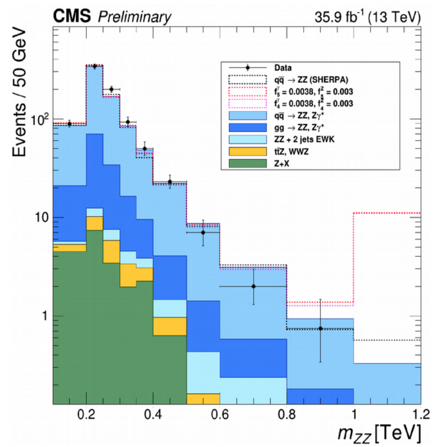
Zγγ, ZZγ, ZZZ couplings zero at tree level in SM

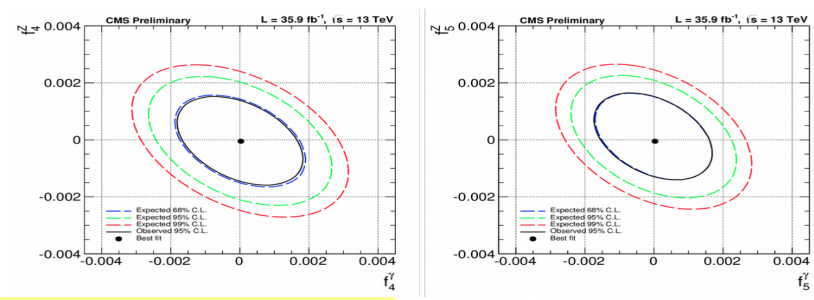
Fits to shape of m_{ZZ} distrib

==> limits on aTGCs

Effective Lagrangian formalism

Nucl Phys B 282 (1987) 253

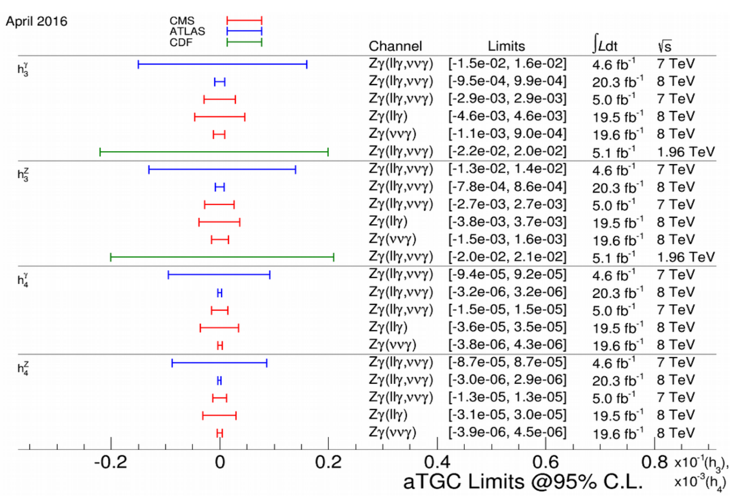




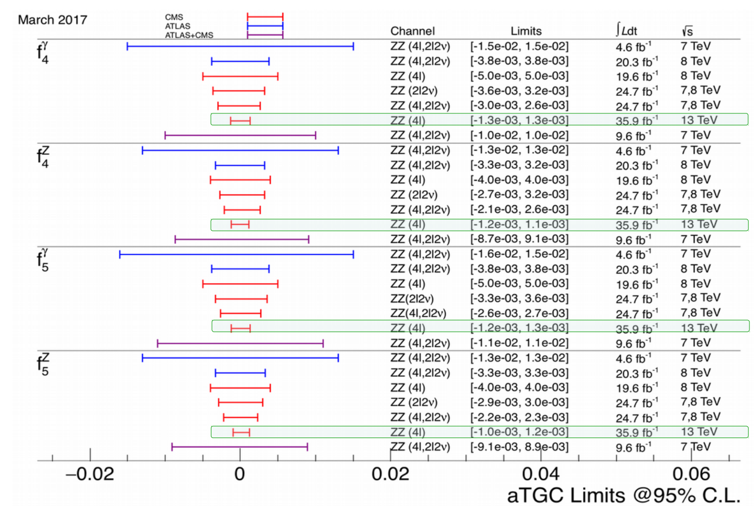
CMS-PAS-SMP-16-017

Zγγ, ZZγ: no 13 TeV results yet

ZZZ, ZZγ



New CMS 13 TeV ZZ → 4ℓ results ==> significantly better limits



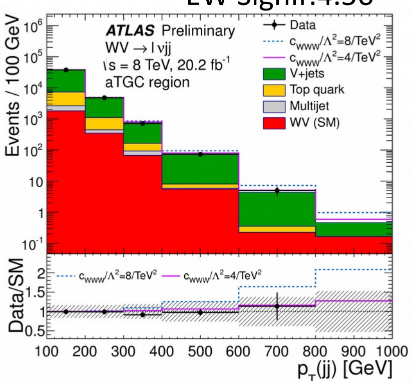
Charged aTGC: WV → ℓνqq

new

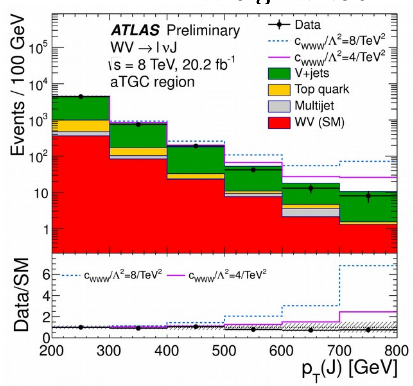
New semi-leptonic WW/WZ analyses use merged jets

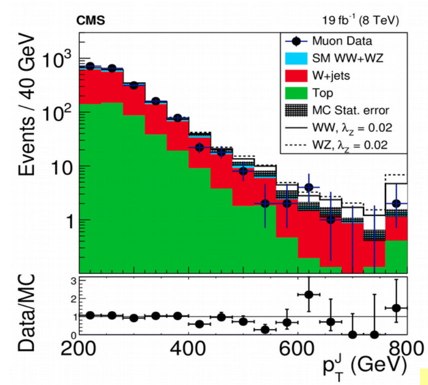
- More sensitivity to aTGCs in merged jets despite lower EW cross-section significance

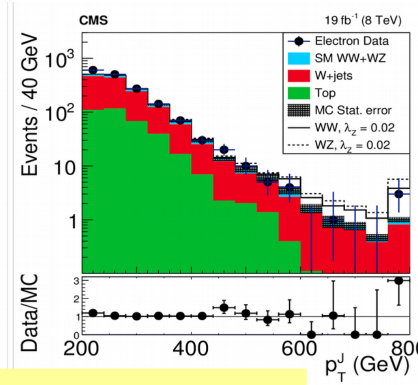
EW Signif:4.5σ



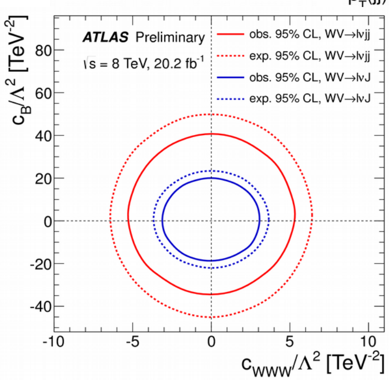
EW Signif:1.3σ







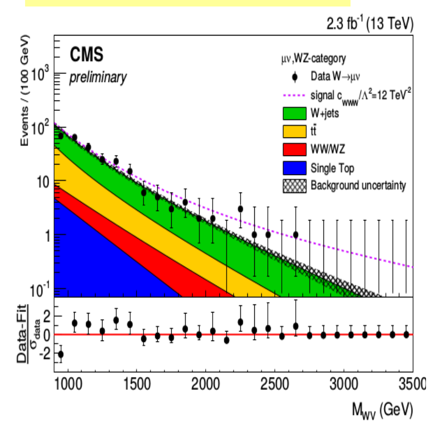
arXiv:1703.06095



ATLAS-STDM-2015-23

Δg_1^Z Limits				
FF	Observed	Expected	Observed	Expected
	WV → ℓνjj		WV → ℓνJ	
$\Lambda_{FF} = \infty$	[-0.039,0.059]	[-0.050,0.066]	[-0.033,0.036]	[-0.039,0.042]
Λ_{FF} = 5TeV	[-0.042,0.0640	[-0.055,0.073]	[-0.044,0.048]	[-0.051,0.054]

But note: less sens. to Form Factors in ℓνjj analysis because they probe Lower energy scale



13 TeV result from CMS !

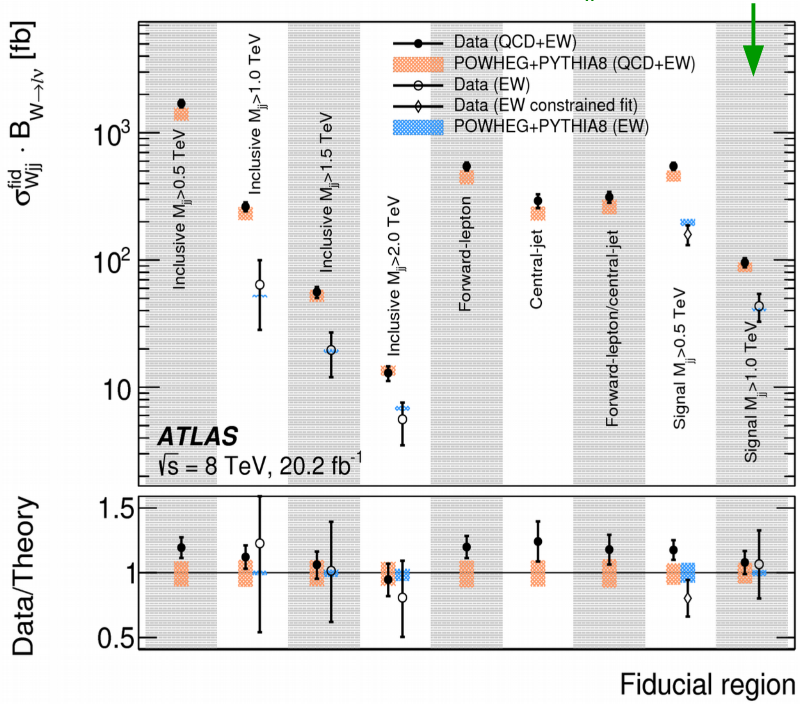
CMS-PAS-SMP-16-012

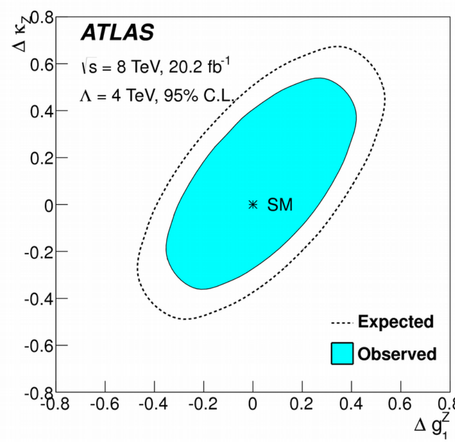
Charged aTGC: Wjj

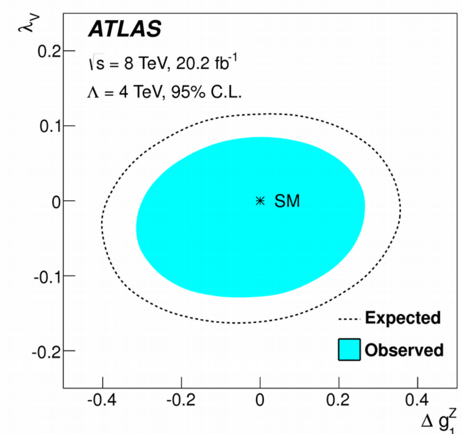
new

New W → eν/μν + 2 forward jets in many fiducial regions with varying EW contrib.

- ATGCs probed using M_{jj} > 1 TeV Signal Region (+ p_T^{j1} > 600 GeV)

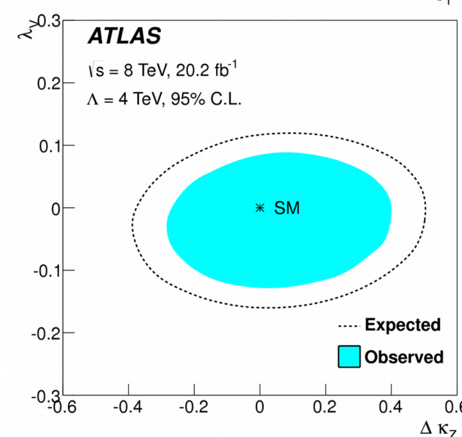






λ_V limits competitive with those from WW production

	Λ = 4 TeV		Λ = ∞	
	Expected	Observed	Expected	Observed
Δg_1^Z	[−0.39, 0.35]	[−0.32, 0.28]	[−0.16, 0.15]	[−0.13, 0.12]
$\Delta\kappa_Z$	[−0.38, 0.51]	[−0.29, 0.42]	[−0.19, 0.19]	[−0.15, 0.16]
λ_V	[−0.16, 0.12]	[−0.13, 0.090]	[−0.064, 0.054]	[−0.053, 0.042]
$\tilde{\kappa}_Z$	[−1.7, 1.8]	[−1.4, 1.4]	[−0.70, 0.70]	[−0.56, 0.56]
$\tilde{\lambda}_V$	[−0.13, 0.15]	[−0.10, 0.12]	[−0.058, 0.057]	[−0.047, 0.046]

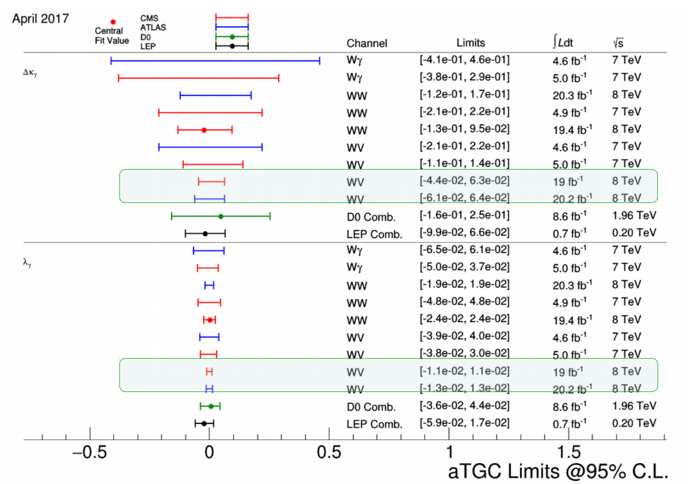


arXiv:1703.04362

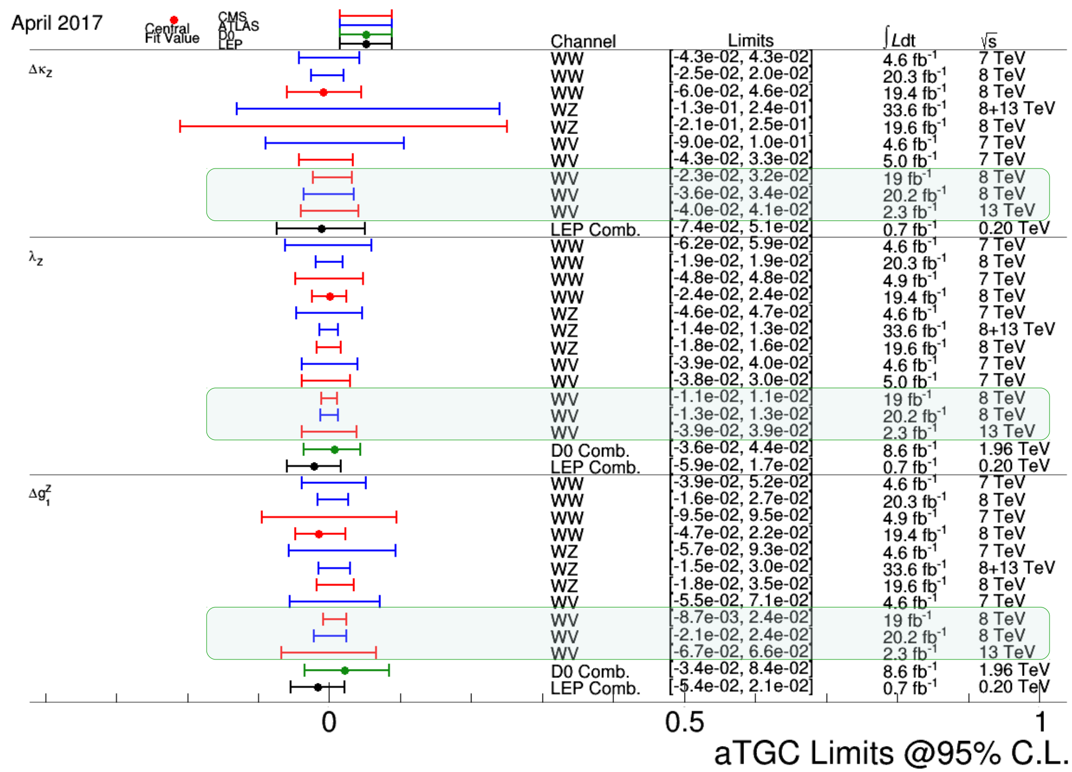
Charged aTGC: Summaries

CMS WV semileptonic 13 TeV results (2.3 fb^{-1}) nearly competitive with 8 TeV (20 fb^{-1})

WWγ Couplings



WWZ Couplings



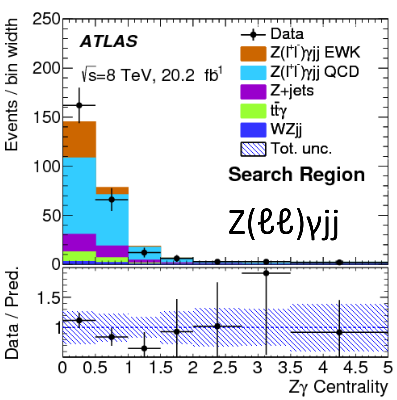
aQGC: New Diboson Results

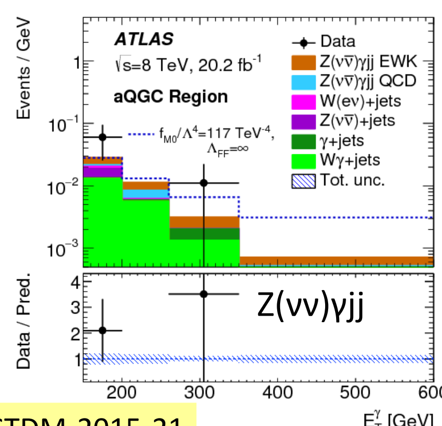
- New W/Zγ and W±W± results all with EW cross-section significances near or above 3σ
  - Note that aQGC fits use more more restrictive phase space with higher S/B but lower signal significance

8 TeV	ATLAS		CMS	
Channel	EW Signal Significance	aQGC Extraction	EW Signal Significance	aQGC Extraction
Zγjj	2.0σ (1.8σ exp) STDM-2015-21	N events in aQGC region	3.0σ (2.0σ exp) arXiv:1702.03025	Fit to $M_{Z\gamma}$ distribution
Wγjj	---	---	2.7σ (1.5σ exp) arXiv:1612.09256	Fit to p_T^W distribution
W±W±jj	3.6σ (2.8σ exp) arXiv:1611.02428	N events in aQGC region	1.9σ (2.9σ exp) PRL 114, 051801 (2015)	Fit to $m_{\ell\ell}$ distribution

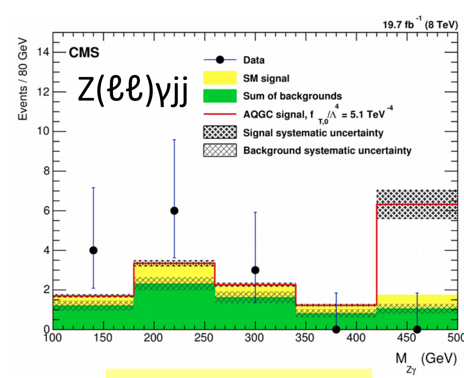
Best Zγjj limits from ν channel

- Improved by 10-30% with inclusion of ℓ modes

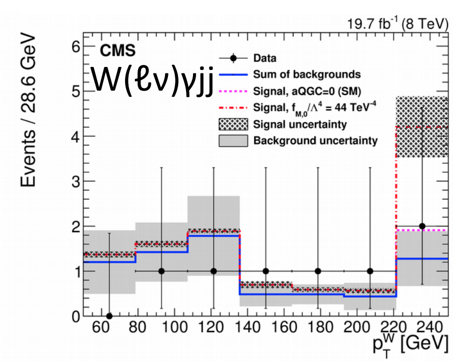




ATLAS-STDM-2015-21



ArXiv: 1702.03025



ArXiv: 1612.09256

aQGC: New Triboson Results

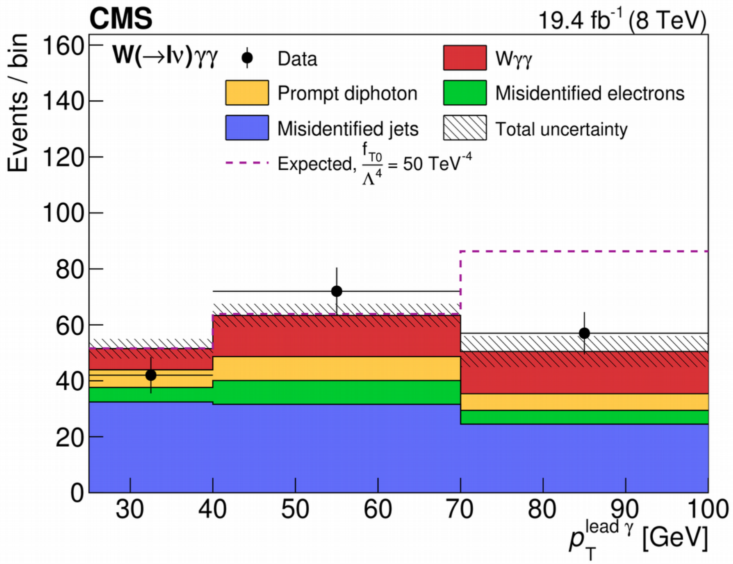
new

New CMS W(ℓν)γγ / Z(ℓℓ)γγ production measurements at 8 TeV

– Signal Significances: 2.6σ (W) / 5.9σ (Z)

Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$Z\gamma\gamma \to e^{+}e^{-}\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \mu^{+}\mu^{-}\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb

Channel	Prediction
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	4.8 ± 0.5 fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	13.0 ± 1.5 fb



– Fiducial cross-sections consistent w/ NLO theory

– aQGC limits (esp. f_{T0}) improved wrt previous 8 TeV results

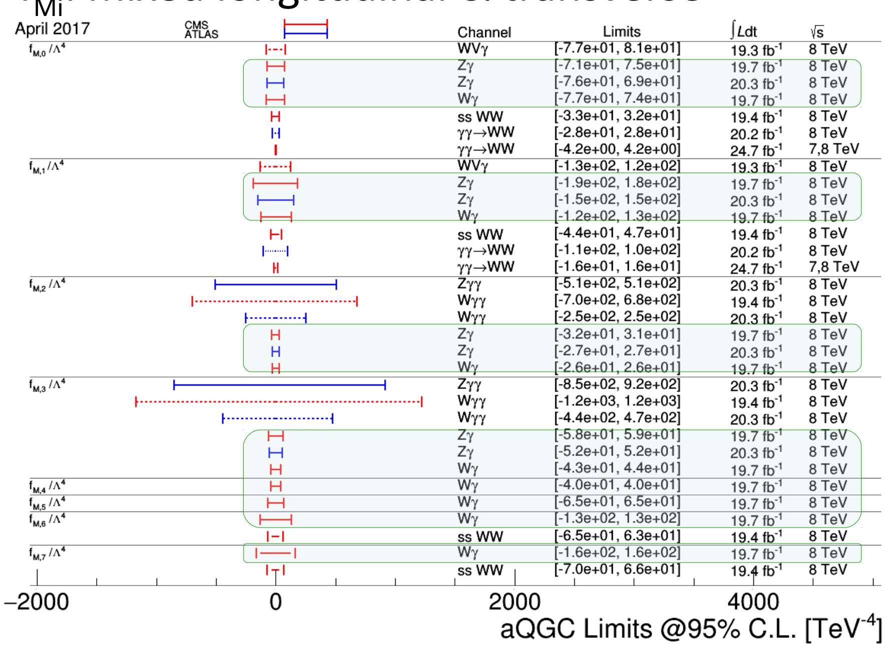
$W\gamma\gamma$	Expected (TeV^{-4})	Observed (TeV^{-4})
$f_{M,2}/\Lambda^4$	$[-549, 531]$	$[-701, 683]$
$f_{M,3}/\Lambda^4$	$[-916, 950]$	$[-1170, 1220]$
$f_{T,0}/\Lambda^4$	$[-26.5, 27.0]$	$[-33.5, 34.0]$
$f_{T,1}/\Lambda^4$	$[-34.5, 34.8]$	$[-44.3, 44.8]$
$f_{T,2}/\Lambda^4$	$[-74.6, 73.7]$	$[-93.8, 93.2]$

aQGC: Summaries

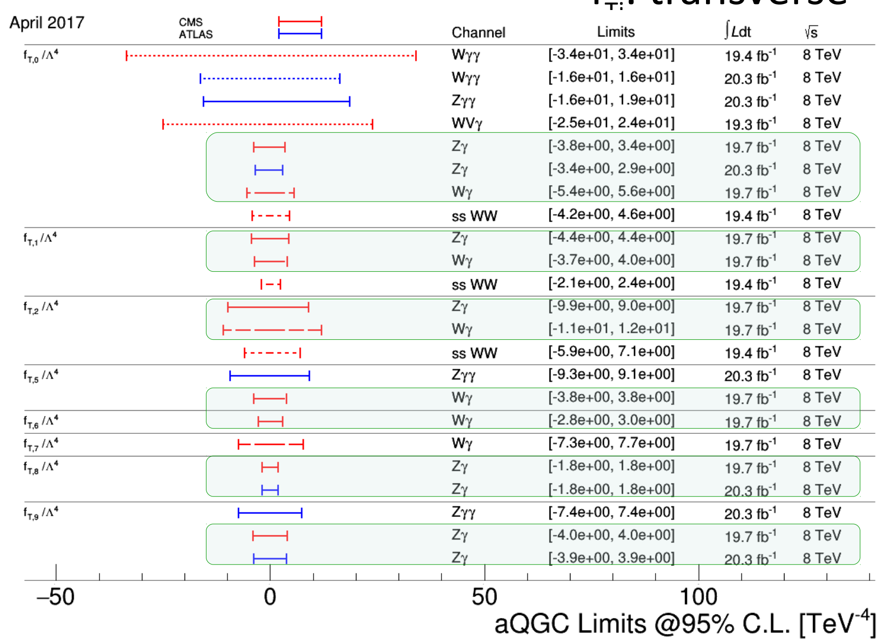
New 8 TeV W/Zγ jj results ==> significantly improved limits

- Eagerly awaiting first 13 TeV results

f_{Mi}: mixed longitudinal & transverse



f_{Ti}: transverse



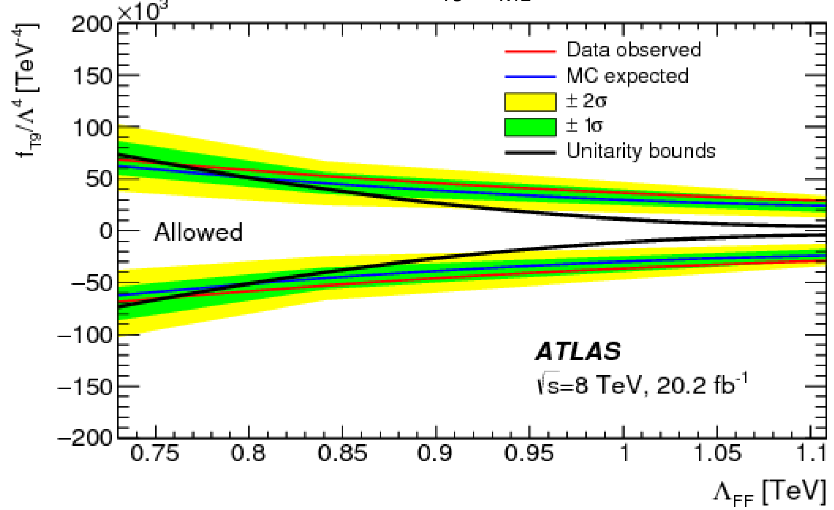
Form Factors

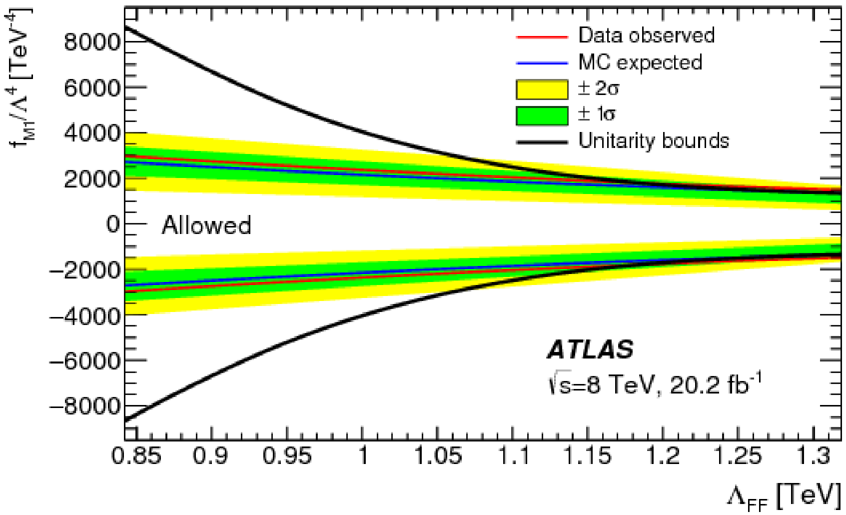
aQGCs: f_{T9}, f_{M1} from ATLAS Zγjj

Inclusion of Form Factors dilutes limits

- e.g. aTGC limits from ATLAS 8 TeV WV → ℓνqq increase by up to 10% for $\Lambda_{FF} = \infty \rightarrow 5$ TeV

- However, many limits without FFs fall in the unitary unsafe region (at 8 TeV)

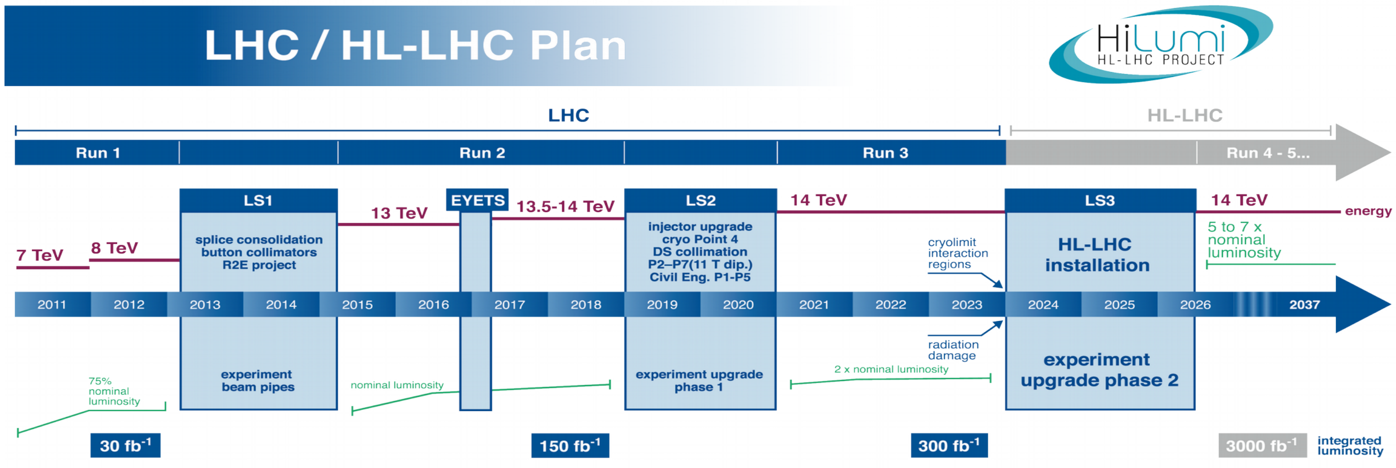




ATLAS-STDM-2015-21

Future Prospects

Upgrade Plans



Drivers of the Upgrades

- Radiation: tracking systems, some muon (ATLAS) & calorimeter (CMS) detectors, electronics
- Event Complexity (pileup): trigger & DAQ systems, electronics

High-Level Goals of the Upgrades (Phase-1 & HL-LHC)

- Maintain performance of object (e,μ,τ,jet,E_t^{miss},...) identification/reconstruction at Run-1 levels in the challenging HL-LHC environment
  ==> very stringent requirements on detectors, electronics, trigger, readout

Diboson Projections

Important Considerations for Diboson/Gauge Coupling Analyses

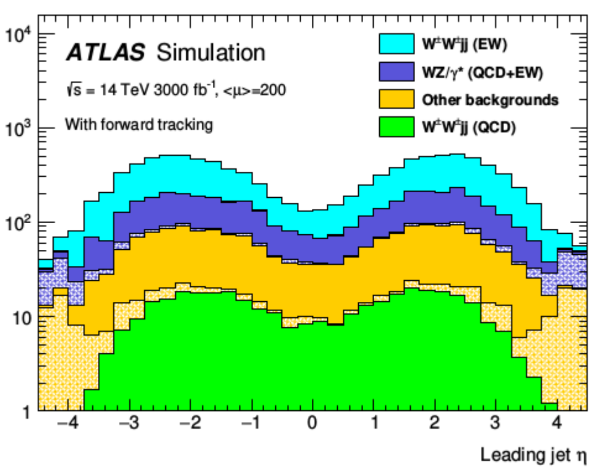
- Lepton triggering: complete overhaul of trigger systems
- Pileup rejection for forward jets: extend tracking |η| = 2.5 → 4.0

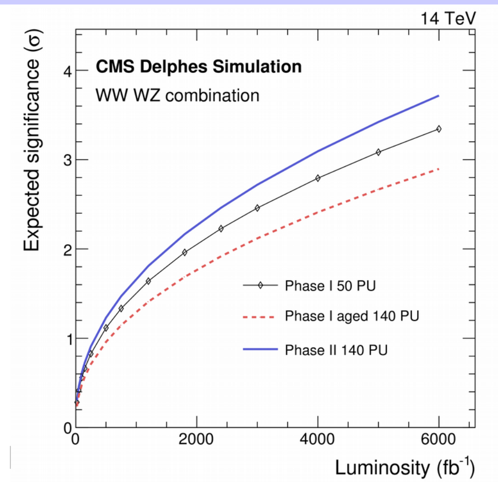
Both ATLAS & CMS have made diboson projections

- Input to HL-LHC detector design/optimization

	ATLAS ($W^\pm W^\pm jj$)		CMS ($W^\pm W^\pm jj$)	CMS (LL $W^\pm W^\pm jj$ + WZjj)
√s / Lumi	8 TeV / 20 fb^{-1}	14 TeV / 3000 fb^{-1}	8 TeV / 19 fb^{-1}	14 TeV / 3000 fb^{-1}
Δσ/σ	36%	4.5%	66% (1.9σ)	(2.75σ)
Reference	ArXiv:1611.02428	ATL-TDR-025 (2017)	PRL 114 (2015)	SMP-14-008 (2016)

ATLAS-TDR-025





SMP-14-008

Conclusion

Diboson measurements provide a very sensitive test of the SM

- Higher order QCD calculations: inclusive & differential cross-sections
- EW symmetry breaking mechanism: TGCs and QGCs

NNLO QCD calculations generally improving agreement with data over NLO

- But some areas where problems still seen

Sensitivity to aTGCs and aQGCs improving significantly

- Use of boosted topologies
- Addition of 13 TeV data

Prospects for diboson physics at HL-LHC are bright !

BACKUP

aTGC Coupling Representations

$$g_1^Z = 1 + c_W \frac{m_Z^2}{2\Lambda^2}$$

$$\kappa_\gamma = 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\kappa_Z = 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2}$$

$$\lambda_\gamma = \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}$$

$$g_4^V = g_5^V = 0$$

$$\tilde{\kappa}_\gamma = c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2}$$

$$\tilde{\kappa}_Z = -c_{\tilde{W}}\tan^2\theta_W \frac{m_W^2}{2\Lambda^2}$$

$$\tilde{\lambda}_\gamma = \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2}$$

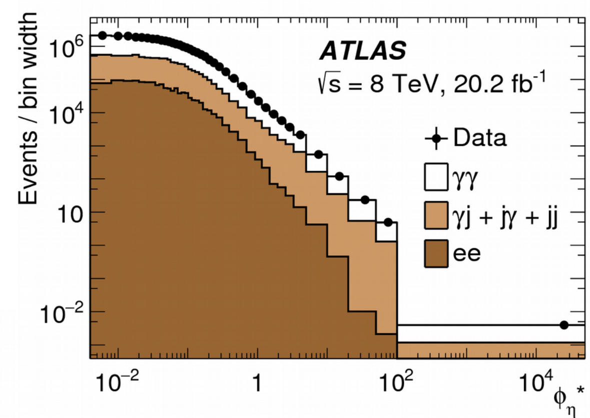
$$\Delta g_1^Z = g_1^Z - 1$$
$$\Delta\kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1$$
$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$$

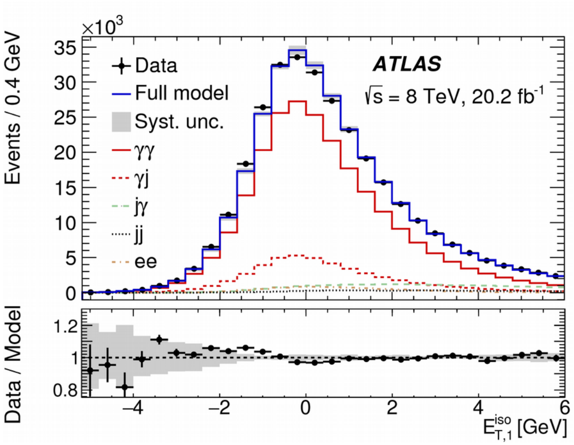
arXiv: 1309.7890

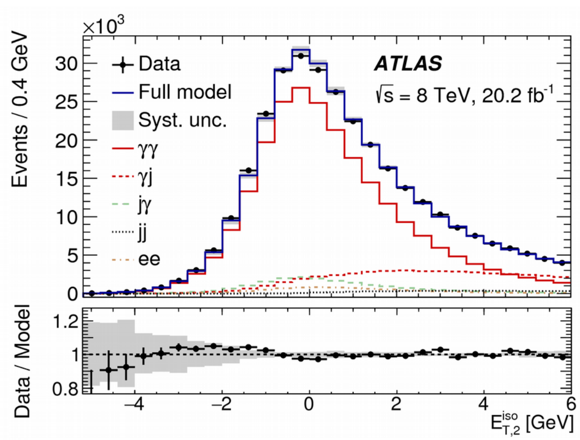
ATLAS γγ – 8 TeV

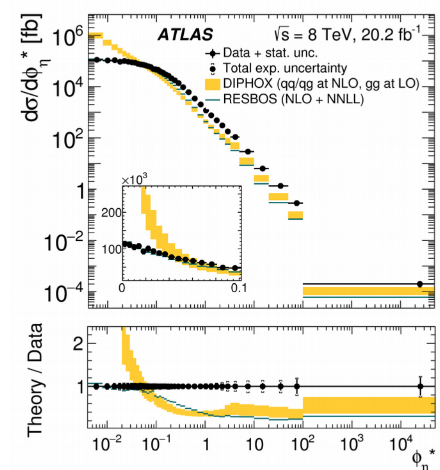
Two methods used to distinguish γγ signal from fake-γ bgrd

- 2D fit to isolation of the two γ's
- matrix method for events that pass/fail isolation requirements
  ==> consistent results









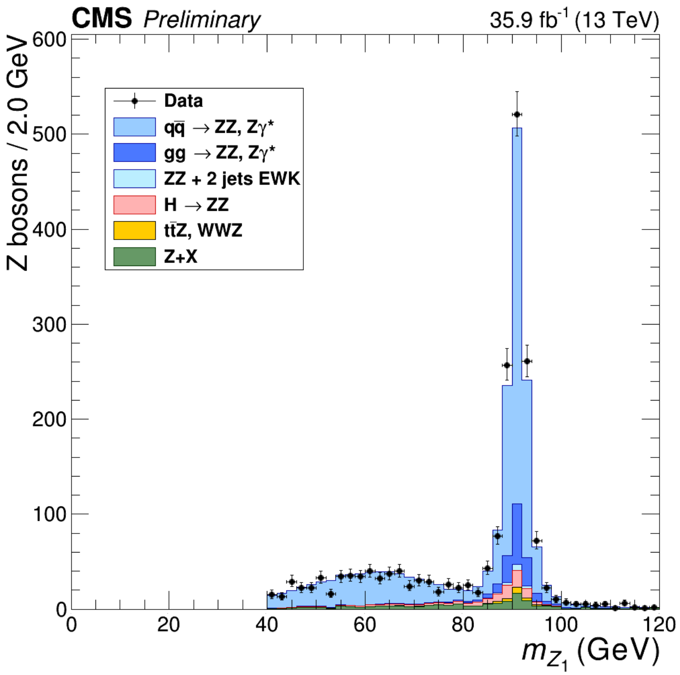
arXiv:1704.03839

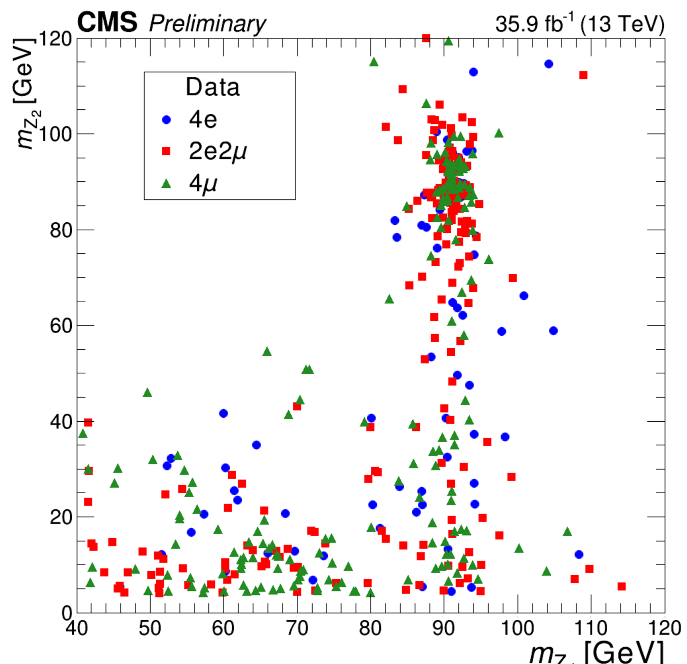
CMS ZZ → 4ℓ – 13 TeV

Tiny background levels in this analysis

- mainly for jet → ℓ mis-ID
- measured using a sample of Z+$\ell_{candidate}$ events in data
  - with relaxed $\ell_{candidate}$ ID

Decay channel	Expected $N_{4\ell}$	Background	Total expected	Observed
4μ	$265.5 \pm 1.3 \pm 8.4$	$5.2 \pm 0.8 \pm 1.5$	$270.7 \pm 1.5 \pm 8.6$	290
$2e2\mu$	$425.4 \pm 1.6 \pm 17.5$	$19.0 \pm 1.8 \pm 3.4$	$444.4 \pm 2.4 \pm 18.1$	465
4e	$165.3 \pm 1.0 \pm 10.9$	$11.8 \pm 1.5 \pm 2.2$	$177.2 \pm 1.8 \pm 11.4$	175
Total	$856.2 \pm 2.3 \pm 33.3$	$36.0 \pm 2.5 \pm 6.4$	$892.2 \pm 3.4 \pm 34.4$	930





CMS-PAS-SMP-16-017

ATLAS WW → eνμν – 13 TeV

Fiducial Cross-Section definition

- mainly for jet → ℓ mis-ID

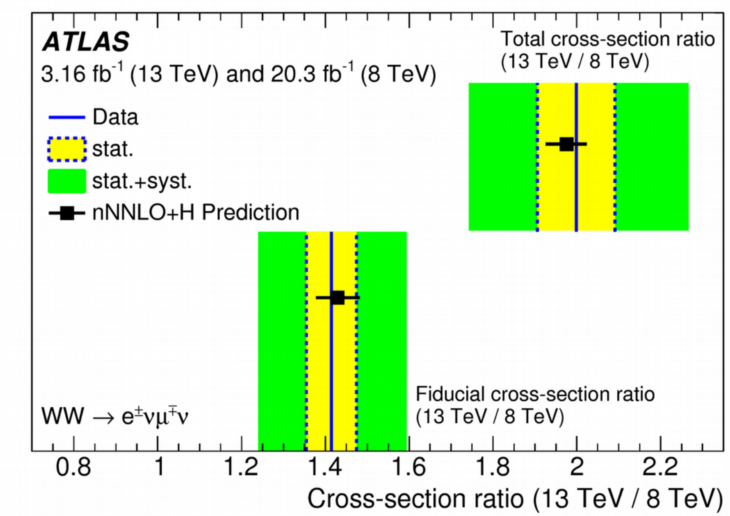
Fiducial selection requirement	Cut value
p_{T}^{ℓ}	> 25 GeV
$\lvert\eta_{\ell}\rvert$	< 2.5
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.5(4.5)$	0
$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}}$	> 15 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 20 GeV

nNNLO prediction

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

- A = (16.4±0.9)%
  also calculated using MC
  > POWHEG-BOX+PYTHIA for qq and gg→H→WW
  > SHERPA for non-res gg

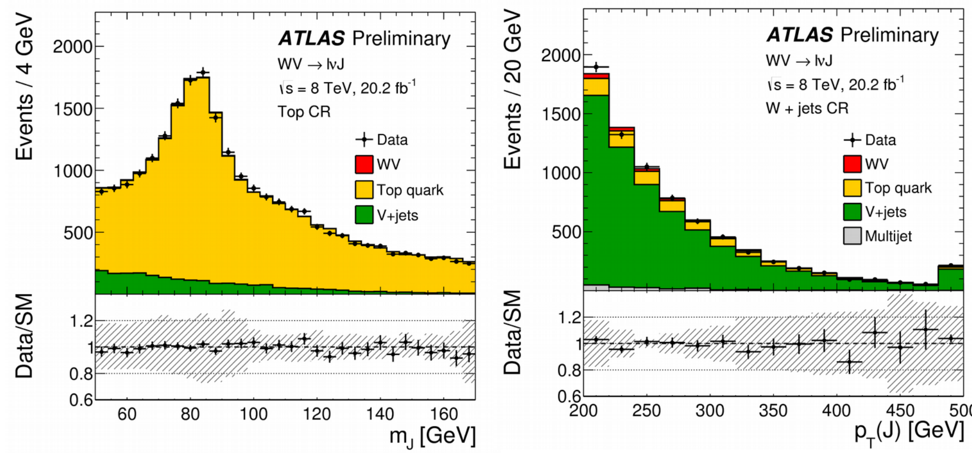
13 TeV / 8 TeV x-sect ratio



ATLAS WV → ℓνqq – 8 TeV

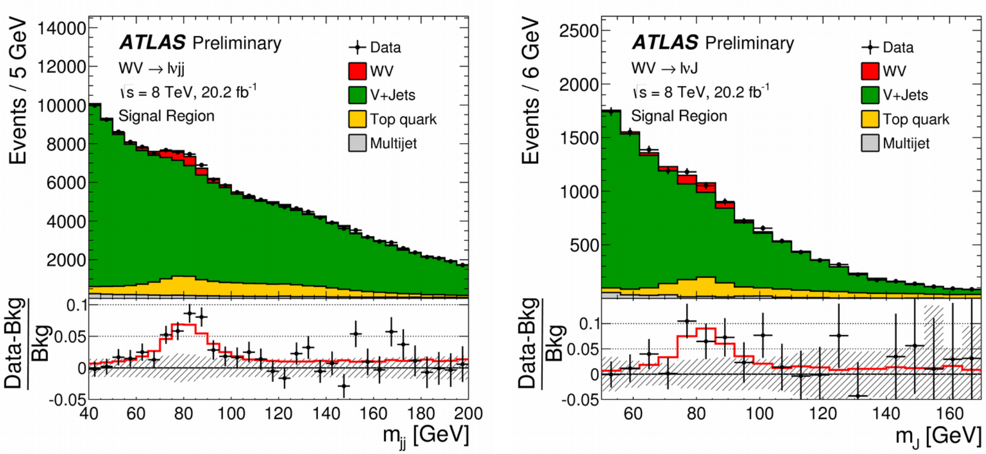
Background Control Regions

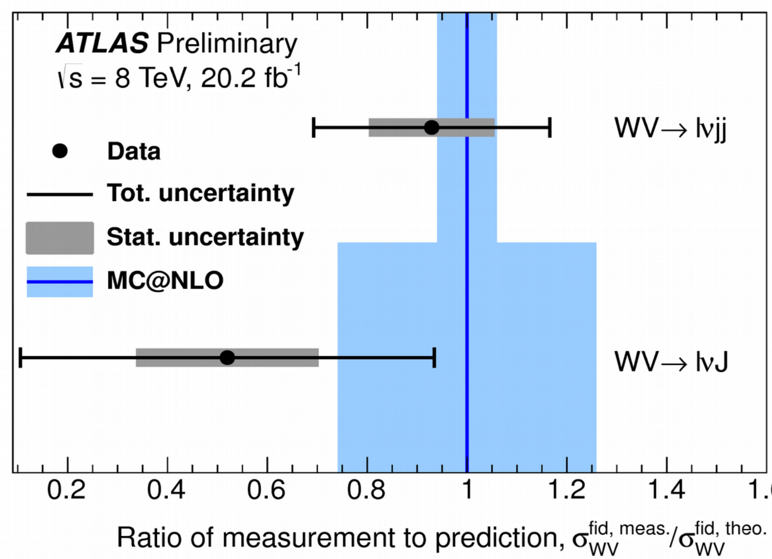
- top & V+jets bgrds



Fiducial Cross-Sections

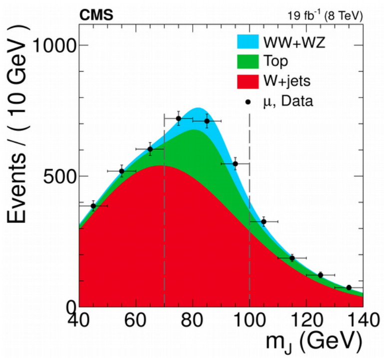
	$WV \to \ell\nu jj$	$WV \to \ell\nu J$
Lepton	$N_\ell = 1$ with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.47$	
	$\Delta R(\ell, j) > 0.4$	$\Delta R(\ell, j) > 0.4$
$W \to \ell\nu$	$p_T(\ell\nu) > 100$ GeV	–
	$m_T > 40$ GeV	–
E_T^{miss}	$E_T^{miss} > 40$ GeV	$E_T^{miss} > 50$ GeV
Jet	$N_j = 2$ with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$	$N_J = 1$ with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$
	$\Delta R(j, e) > 0.2$	$\Delta R(J, \ell) > 1.0$
		No small-R jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.5$
		$\Delta R(j, J) > 1.0$, $\Delta R(j, e) > 0.2$
	$40 < m_{jj} < 200$ GeV	$50 < m_J < 170$ GeV
	$p_T(jj) > 100$ GeV	–
	$\Delta\eta(j, j) < 1.5$	–
Global	$\Delta\phi(j_1, E_T^{miss}) > 0.8$	–

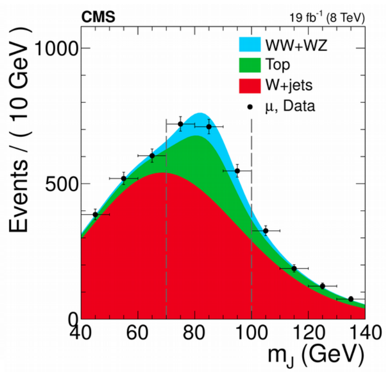


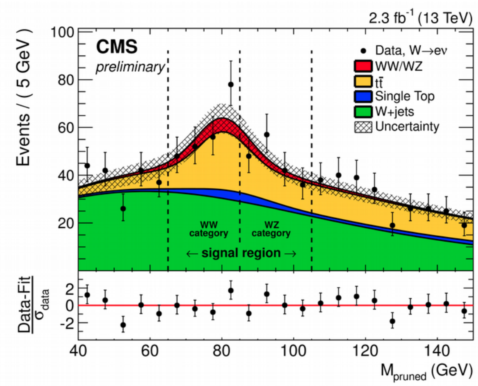


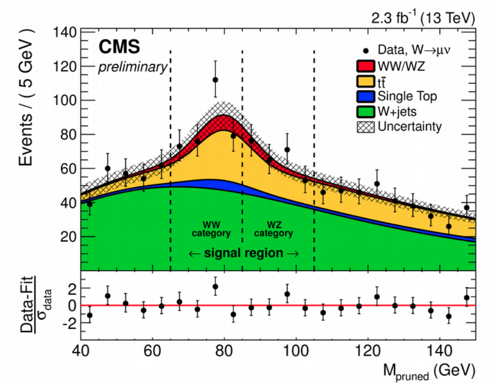
CMS WV → ℓνqq – 8,13 TeV

W+jets, tt, diboson normalizations from fits to m_J distributions









Fits for aTGCs from p_T^J (8 TeV) & m_{WV} (13 TeV) distributions

8 TeV

- top & diboson shapes from MC (diboson adjusted for aTGCs)
- W+jets shapes from MC corrected using sideband data transfer func.

13 TeV

Parameter	Expected Limits	Observed Limits
λ_Z	$[-0.014, 0.013]$	$[-0.011, 0.011]$
$\Delta\kappa_\gamma$	$[-0.068, 0.082]$	$[-0.044, 0.063]$
Δg_1^Z	$[-0.018, 0.028]$	$[-0.0087, 0.024]$

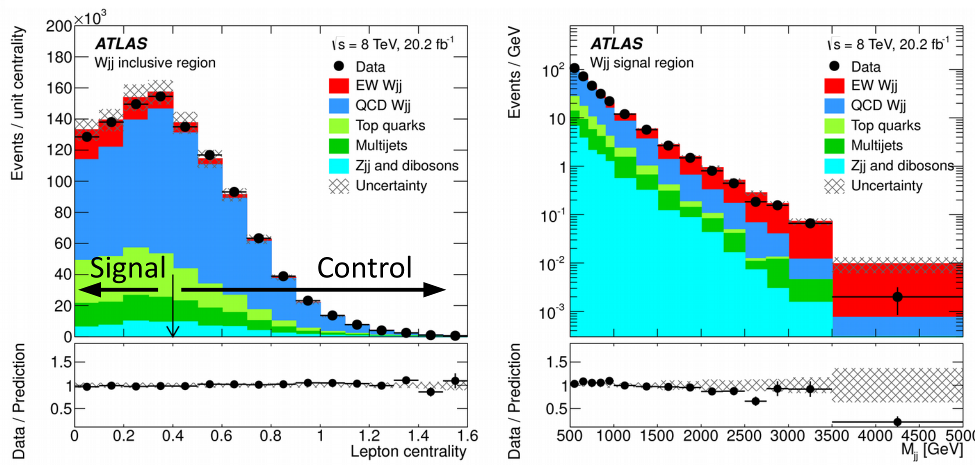
	aTGC	expected limit	observed limit
EFT param.	$\frac{c_{WWW}}{\Lambda^2}$ (TeV^{-2})	[-8.73 , 8.70]	[-9.46 , 9.42]
	$\frac{c_W}{\Lambda^2}$ (TeV^{-2})	[-11.7 , 11.1]	[-12.6 , 12.0]
	$\frac{c_B}{\Lambda^2}$ (TeV^{-2})	[-54.9 , 53.3]	[-56.1 , 55.4]
Vertex param.	λ	[-0.036 , 0.036]	[-0.039 , 0.039]
	Δg_1^Z	[-0.066 , 0.064]	[-0.067 , 0.066]
	$\Delta\kappa_Z$	[-0.038 , 0.040]	[-0.040 , 0.041]

ATLAS Wjj – 7,8 TeV

Fiducial Cross-Section measurements for QCD & EW components

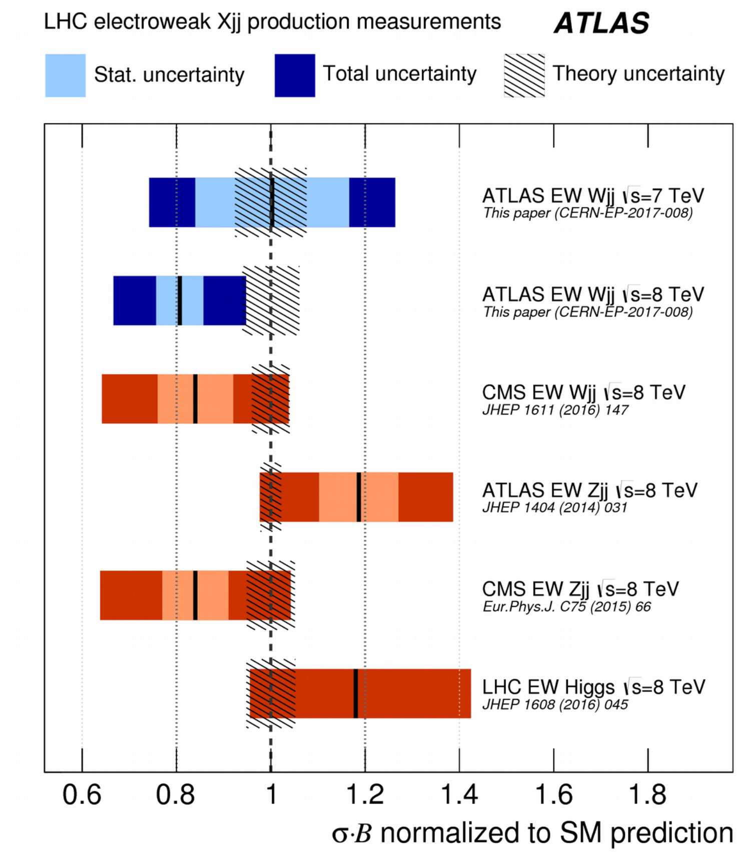
- uses M_{jj} as discriminating distribution
- shape of QCD M_{jj} distrib from control region (high lepton centrality)

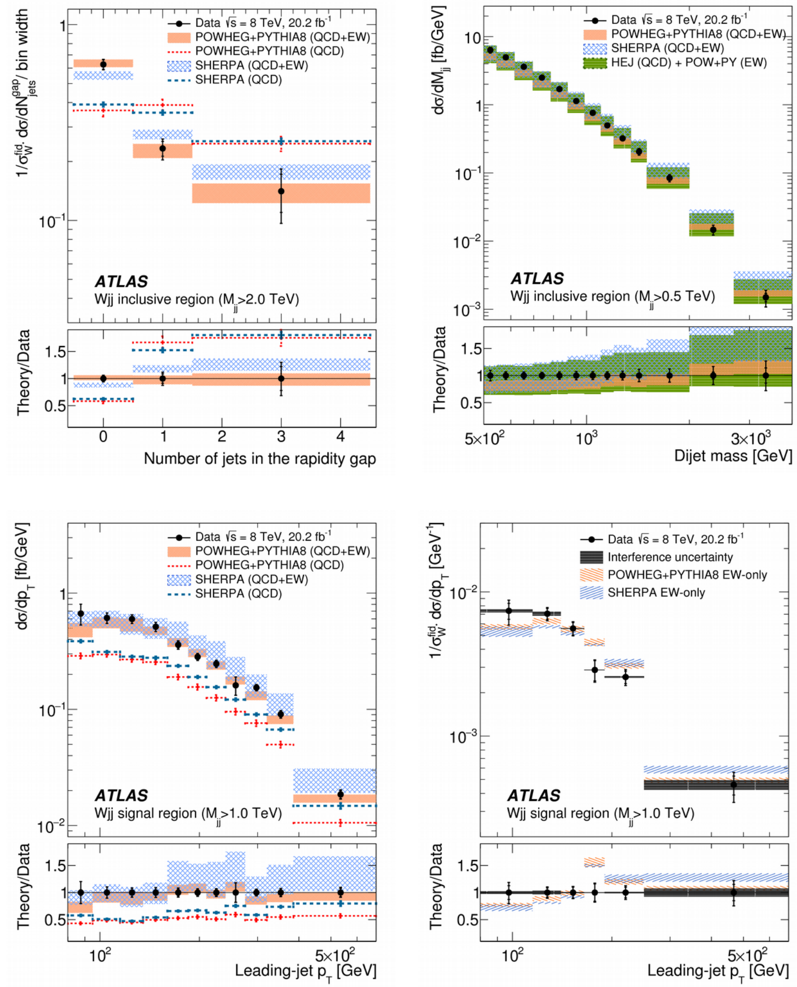
Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV
	Lepton $\lvert\eta\rvert < 2.5$
	$E_T^{miss} > 20$ GeV
	$m_T > 40$ GeV
	$p_T^{j_1} > 80$ GeV
	$p_T^{j_2} > 60$ GeV
	Jet $\lvert y\rvert < 4.4$
	$M_{jj} > 500$ GeV
	$\Delta y(j_1, j_2) > 2$
	$\Delta R(j, \ell) > 0.3$
Fiducial and differential measurements	
Signal region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Forward-lepton control region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} = 0$
Central-jet validation region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} \geq 1$
Differential measurements only	
Inclusive regions	$M_{jj} > 0.5$ TeV, 1 TeV, 1.5 TeV, or 2 TeV
Forward-lepton/central-jet region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} \geq 1$
High-mass signal region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Anomalous coupling measurements only	
High-q^2 region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0, p_T^{j_1} > 600$ GeV



ATLAS Wjj – 7,8 TeV (cont)

Total & Differential Cross-Sections





arXiv:1703.04362

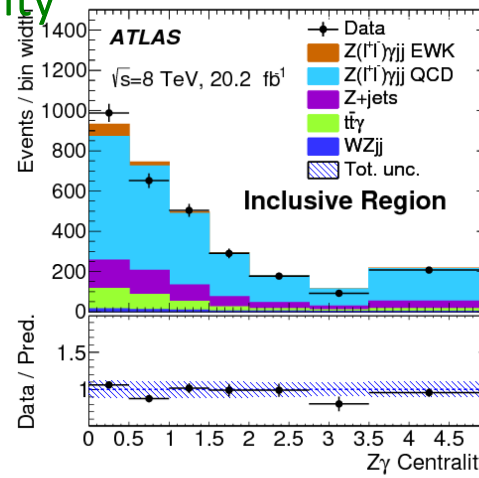
ATLAS Z(ℓℓ/νν)γjj – 8 TeV

Fiducial Cross-Section measurement in Z → ℓℓ channel

- Distinguish EWK from QCD component using centrality

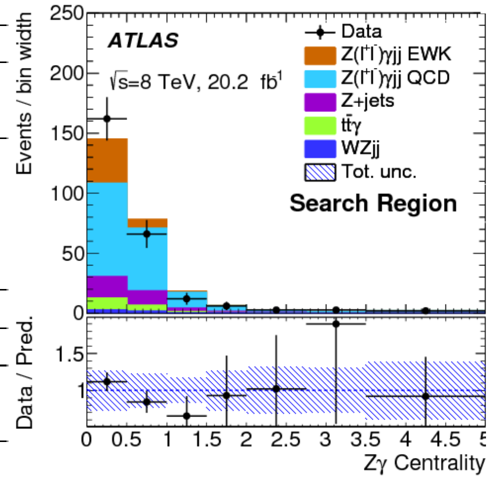
$$\zeta \equiv \left|\frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}}\right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$

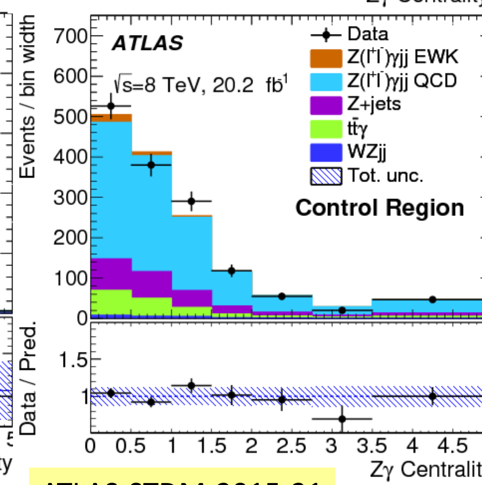
- σ_{EWK}(meas) = 1.1 ± 0.5(stat) ± 0.4(syst) fb
  σ_{EWK}(VBFNLO) = 0.94 ± 0.09 fb



EWK Significance
2.0σ (obs) / 1.8σ (exp)

Objects	Particle- (Parton-) level selection
Leptons	$p_T^\ell > 25$ GeV and $\|\eta^\ell\| < 2.5$ Dressed leptons, OS charge
Photon (kinematics)	$E_T^\gamma > 15$ GeV, $\|\eta^\gamma\| < 2.37$ $\Delta R(\ell,\gamma) > 0.4$
Photon (isolation)	$E_T^{iso} < 0.5 \cdot E_T^\gamma$ (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) $E_T^{j(p)} > 30$ GeV, $\|\eta^{j(p)}\| < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$
Control region (CR)	$150 < m_{jj(pp)} < 500$ GeV
Search region (SR)	$m_{jj(pp)} > 500$ GeV
aQGC region	$m_{jj(pp)} > 500$ GeV $E_T^\gamma > 250$ GeV





ATLAS-STDM-2015-21

CMS Z(ℓℓ)γjj – 8 TeV

Fiducial Cross-Section measurement in Z → ℓℓ channel

– Distinguish EWK from QCD component using fit to M_{jj} distrib

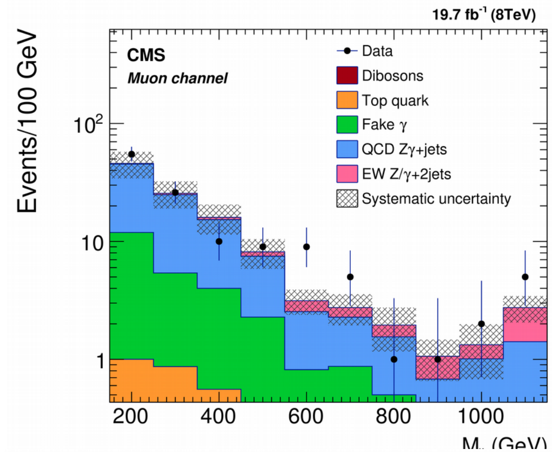
$$\sigma_{EW}(meas)=1.86^{+0.09}_{-0.75}(stat)^{+0.34}_{-0.26}(syst)\pm0.05(lumi)\ \ fb$$

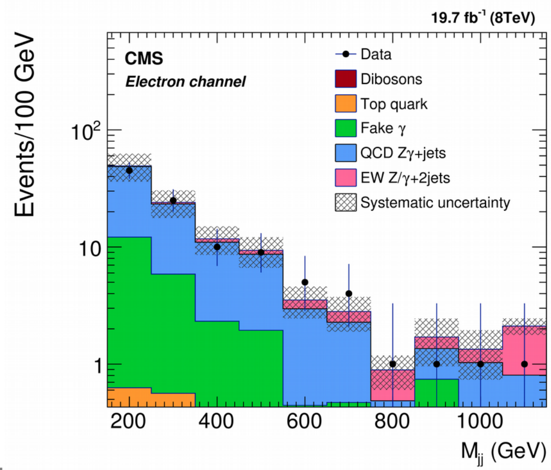
$$\sigma_{EW}(MADGRAPH)=1.27\pm0.11(scale)\pm0.05(PDF)\ \ fb\ \ \ (LO)$$

Common selection
$p_T^{j1,j2} > 30\,\mathrm{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$
$p_T^{\ell1,\ell2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell1,\ell2}\rvert < 2.4$
$\lvert\eta^{\gamma}\rvert < 1.4442$
$M_{jj} > 150\,\mathrm{GeV}$
$70 < M_{\ell\ell} < 110\,\mathrm{GeV}$

EW signal measurement	Fiducial cross section	aQGC search
$p_T^{\gamma} > 25\,\mathrm{GeV}$	$p_T^{\gamma} > 20\,\mathrm{GeV}$	$p_T^{\gamma} > 60\,\mathrm{GeV}$
$\lvert\Delta\eta_{jj}\rvert > 1.6$	$\lvert\Delta\eta_{jj}\rvert > 2.5$	$\lvert\Delta\eta_{jj}\rvert > 2.5$
$\Delta R_{j\ell} > 0.3$, $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$	$\Delta R_{jj,\gamma j,\gamma\ell,j\ell} > 0.4$	$\Delta R_{j\ell} > 0.3$, $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$
$\lvert y_{Z\gamma} - (y_{j1}+y_{j2})/2\rvert < 1.2$	$M_{jj} > 400\,\mathrm{GeV}$	$M_{jj} > 400\,\mathrm{GeV}$
$\Delta\phi_{Z\gamma,jj} > 2.0$ radians		
$M_{jj} > 400\,\mathrm{GeV}$ with two divided regions		
$400 < M_{jj} < 800\,\mathrm{GeV}$ and $M_{jj} > 800\,\mathrm{GeV}$		

EWK Significance
3.0σ (obs) / 2.0σ (exp)



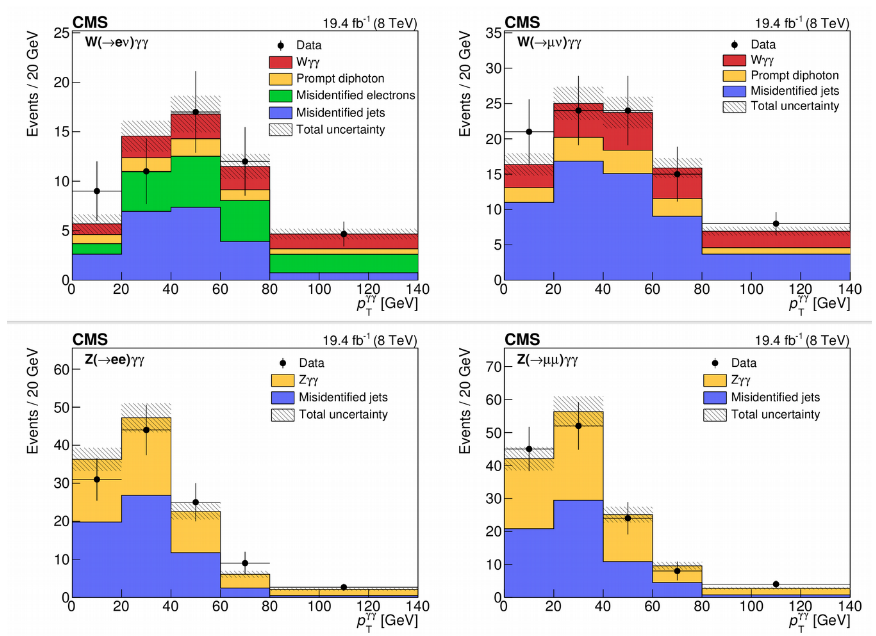


CMS Wγγ/Zγγ – 8 TeV

Fiducial Cross-Section measurement

- Fake photon background (mainly from jets) estimated using 2D distribution of isolation of two photons – tight vs loose selections
  - > templates from MC and data control samples

Definition of the $W\gamma\gamma$ fiducial region
$p_T^\gamma > 25\,\mathrm{GeV}$, $\lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 25\,\mathrm{GeV}$, $\lvert\eta^\ell\rvert < 2.4$
One candidate lepton and two candidate photons
$m_T > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$
Definition of the $Z\gamma\gamma$ fiducial region
$p_T^\gamma > 15\,\mathrm{GeV}$, $\lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 10\,\mathrm{GeV}$, $\lvert\eta^\ell\rvert < 2.4$
Two oppositely charged candidate leptons and two candidate photons
leading $p_T^\ell > 20\,\mathrm{GeV}$
$m_{\ell\ell} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$



Signal Significances: 2.6σ (Wγγ) / 5.9σ (Zγγ) using profile likelihood (data & pred bgrd) for each channel and for both/one photon(s) in barrel