Recent tests of the Standard Model with multi boson final states at the ATLAS detector

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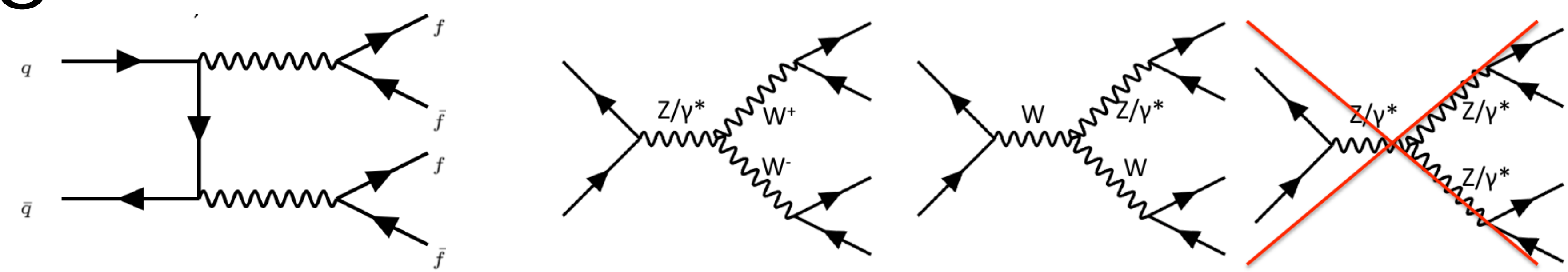
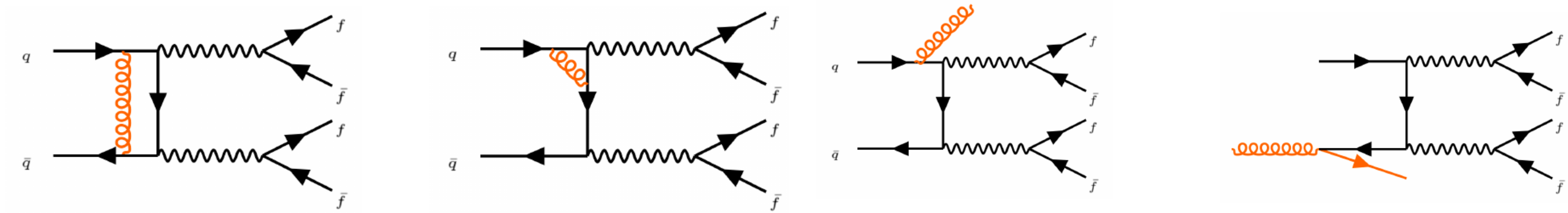
- Standard Model production mechanisms
- BSM production mechanisms
- Diboson production
- Vector Boson Scattering/Fusion
- Multi-Boson production
- Limits on Anomalous Couplings

SM production mechanisms

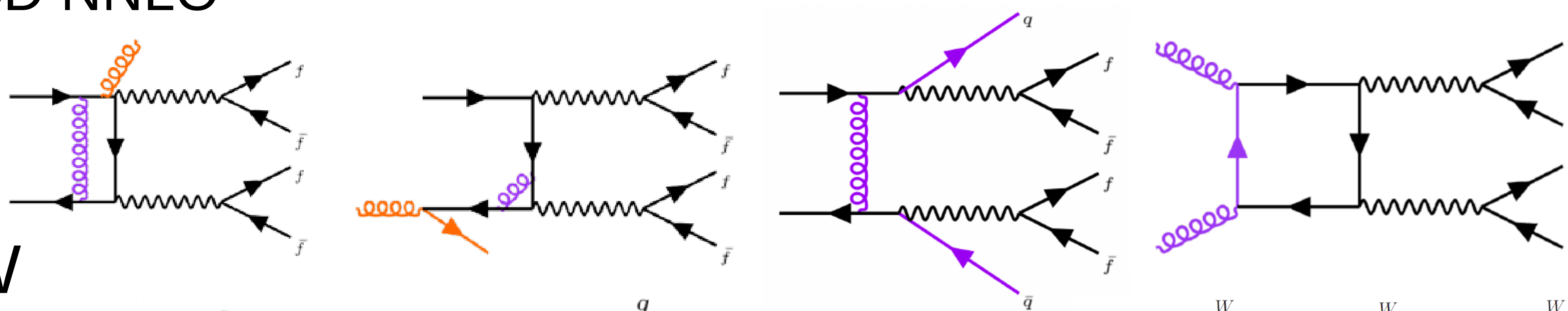
QCD LO



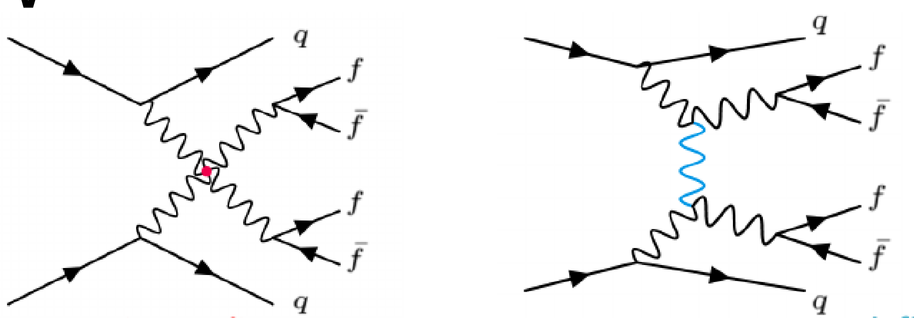
QCD NLO



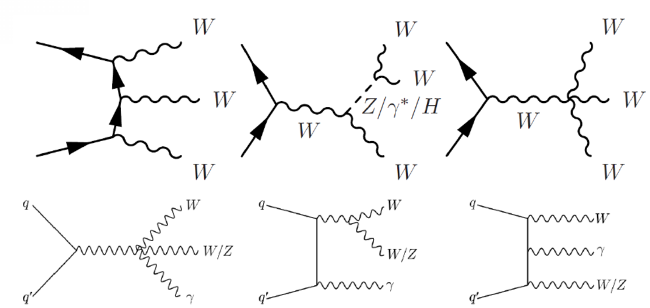
QCD NNLO



EW

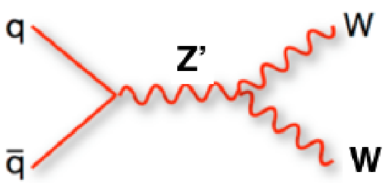


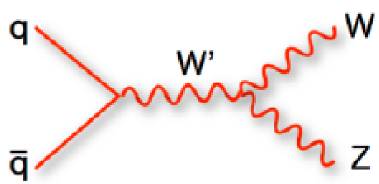
tribosons



(some) BSM production mechanisms

- Heavy vector triplets





Weakly coupled resonances from extensions of the gauge group

Or produced in strong scenarios (like composite Higgs)

Narrow resonances, with neutral or charged final states ex. JHEP 09 (2014) 060

- Warped Extra Dimensions

SM particles in a 5D bulk of a multi-dimensional universe

Predicts a series of Kaluza-Klein gravitons, the lighest at the TeV scale

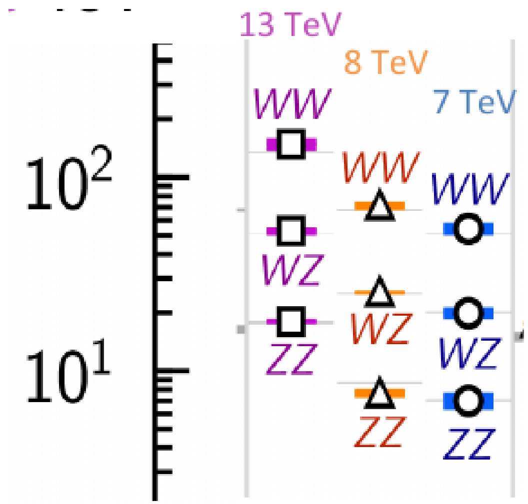
Gluon fusion production

Only neutral final states

Phys. Rev. D, 76.036006

Recent ATLAS direct searches (not covered here)
ATLAS_EXOT-2016-19
ATLAS-CONF-2017-051
ATLAS-EXOT-2016-29
Phys. Lett. B764 (2017) 11-30

Leptonic final state WW, WZ, ZZ at 7, 8, and 13 TeV



Purity:

70%

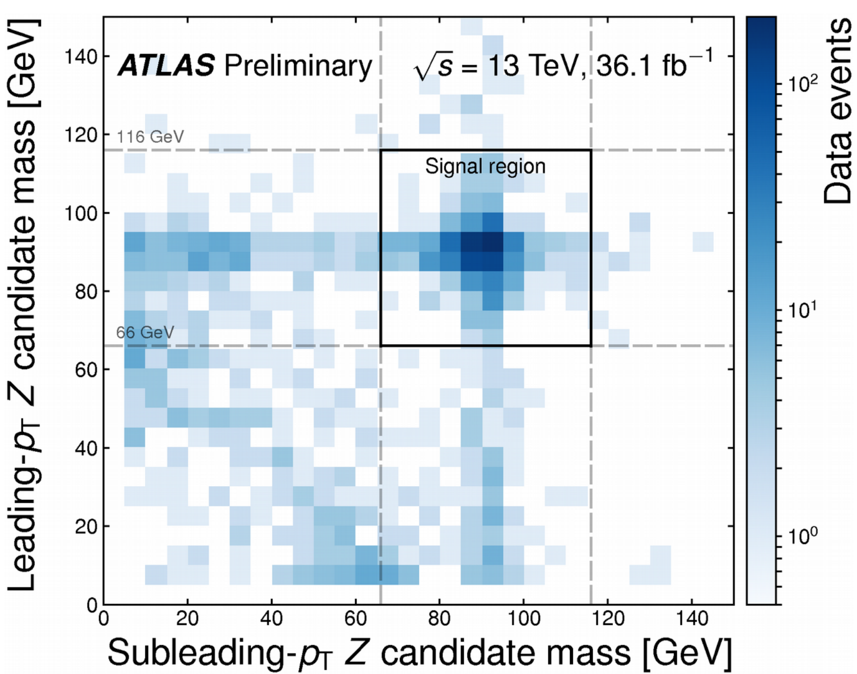
75%

98%

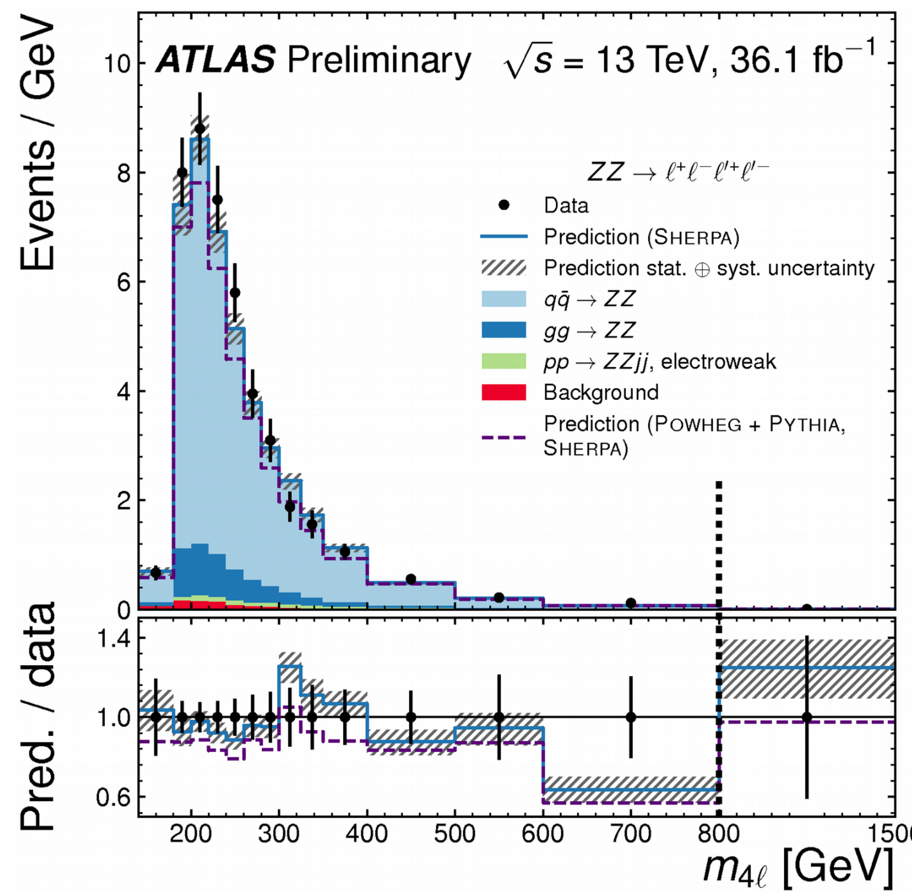
More charged leptons mean cleaner signal but smaller cross-section

Will only present 13 TeV results

ZZ selected in 36.1/fb of 2015 and 2016 data.
Signal region requires at least 4 leptons on Z peak
(but tribosons treated as BG if Nlep != 4)



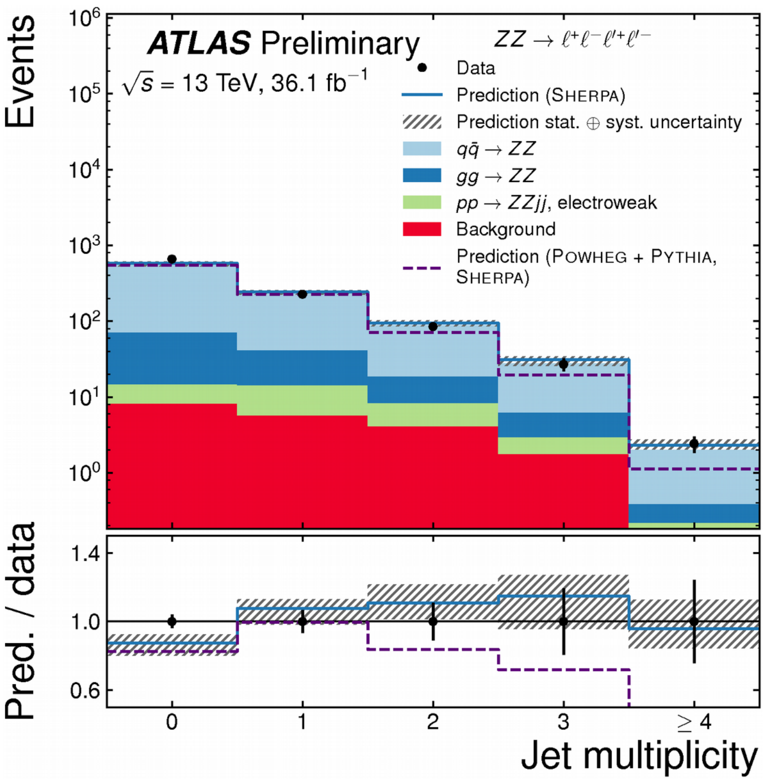
ATLAS-CONF-2017-031



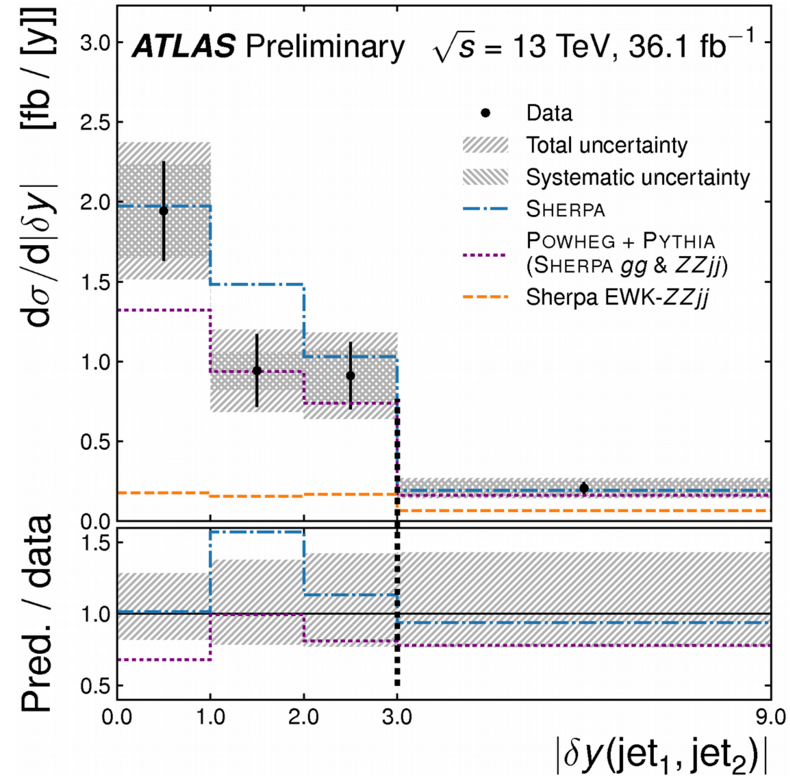
ZZ channel results

ATLAS-CONF-2017-031

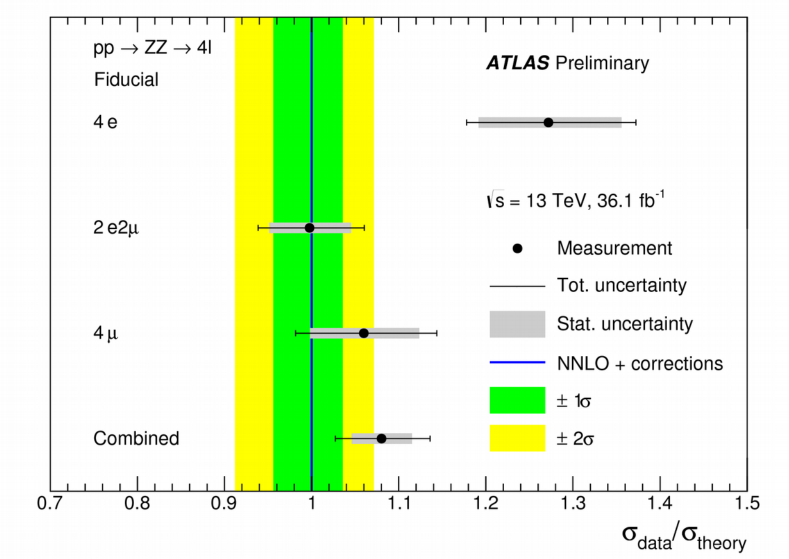
NNLO predictions from MATRIX with nLO EW corrections, NLO corrections for gg initial states, and 4l2j corrections from SHERPA



4l2j corrections important at high jet multiplicity



EW corrections important for dijets with large rapidity difference (enhancement of VBS)

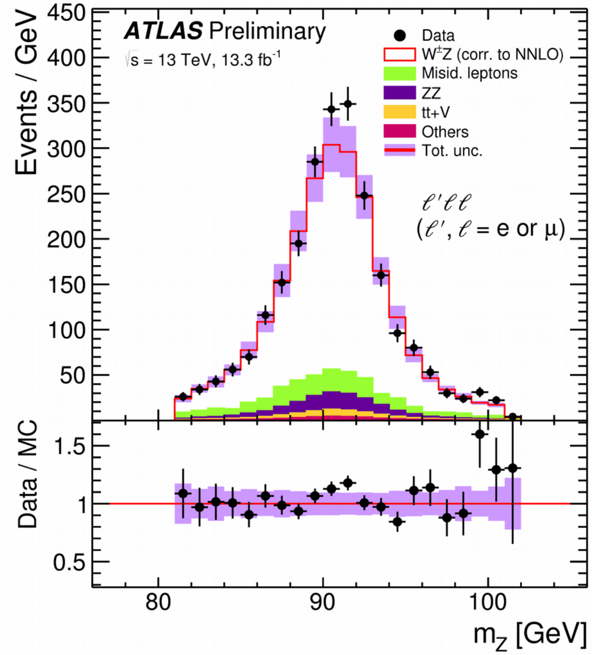


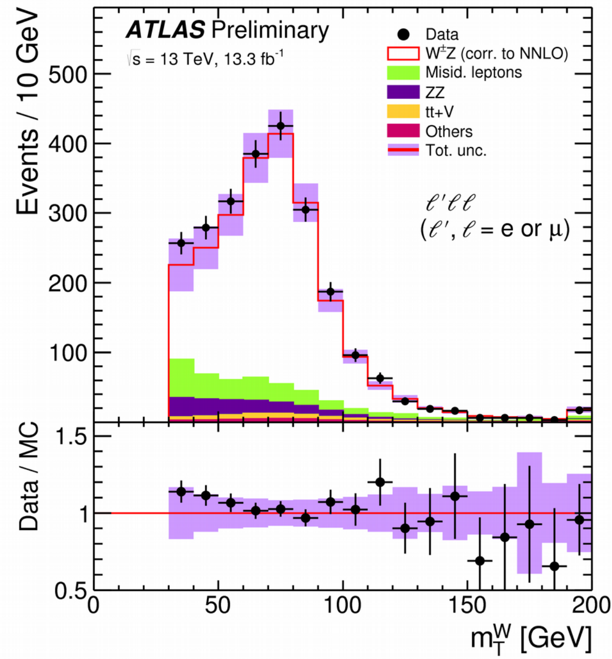
2σ excess in 4e channel, but overall good agreement with predictions

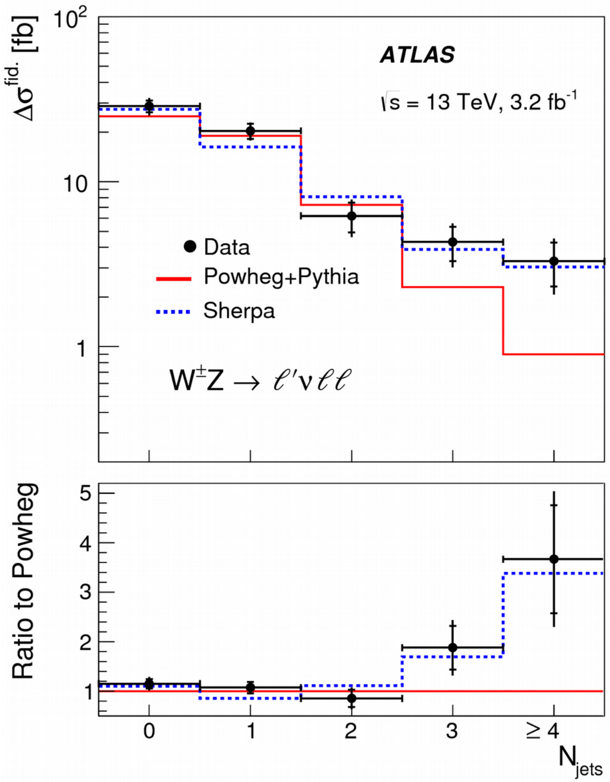
WZ production

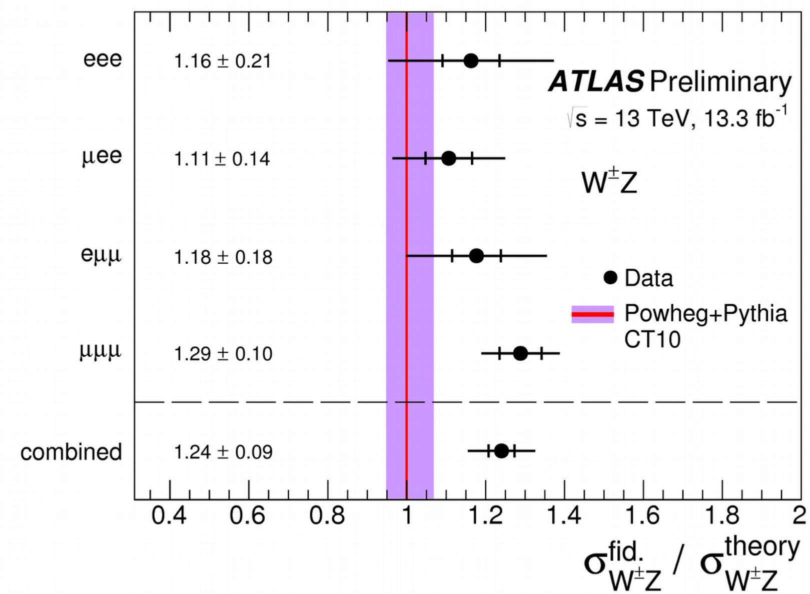
ATLAS-CONF-2016-043 13.3/fb
Phys. Lett. B 762 (2016) 3.2/fb

Results compared to NNLO, NLO (Powheg) and nnLO (Sherpa), important for high jet multiplicities





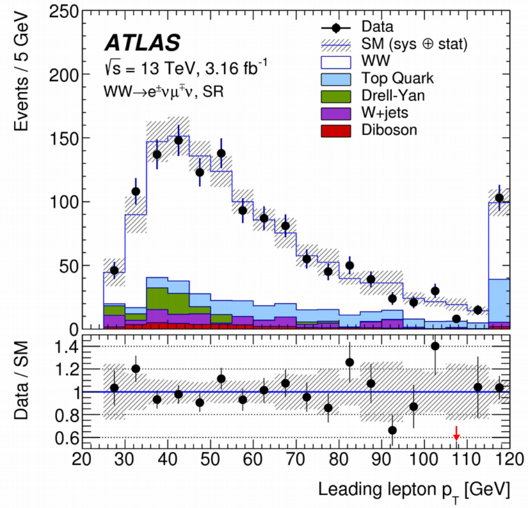


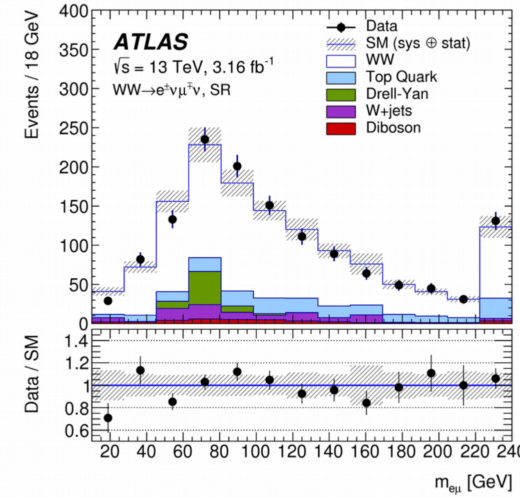


Measured cross-section 2σ higher than NLO, but in better agreement with NNLO (~10% higher, not shown)

WW production

ArXiv:1702.04519 submitted to PLB,
3.16/fb at 13 Tev

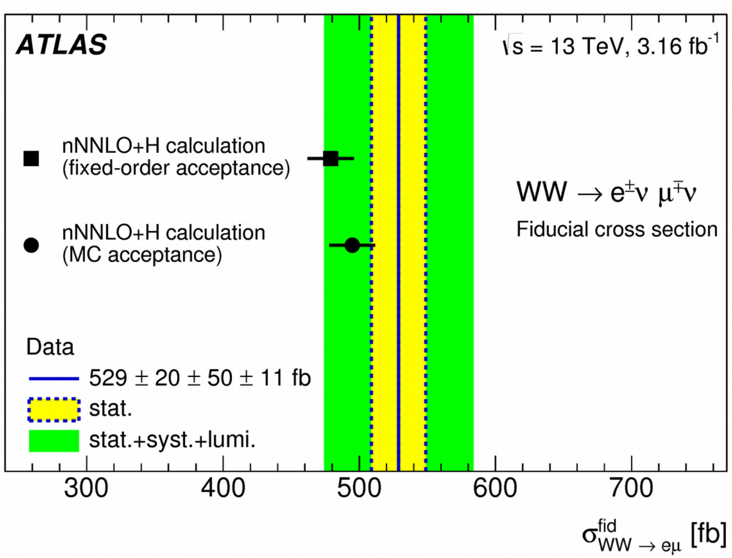


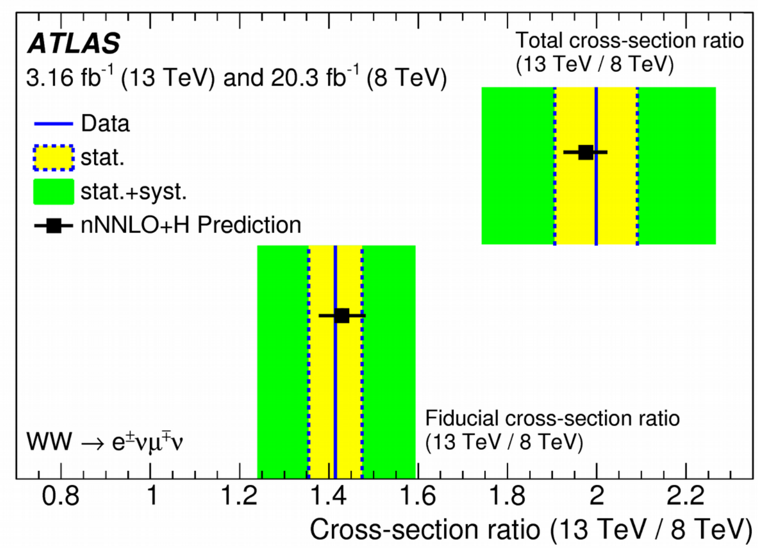


Compare to nNNLO + 8% Higgs contribution (jet veto suppresses top, eμ selection suppresses DY)

Top and DY BG from template fit to control regions (top SF 0.875±0.035)

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





Result smaller than nNNLO + H calculation, similarly to the 8 TeV result

Semileptonic WV at 8 TeV

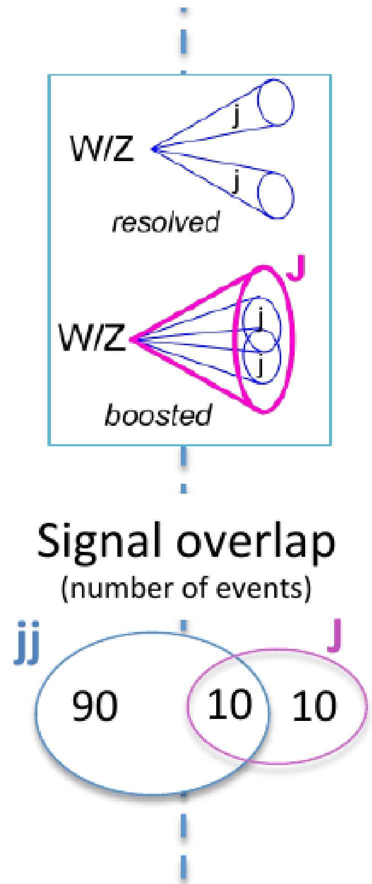
ArXiv:1706.01702, accepted by EPJC

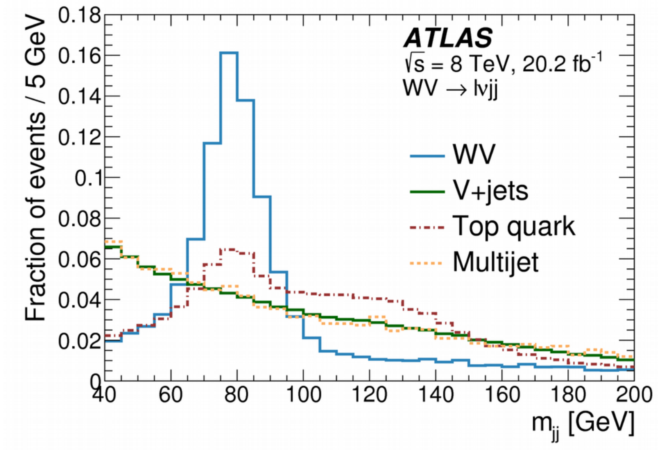
6 times higher BR than leptonic channel, allows kinematic constraints, and higher sensitivity to aTGC

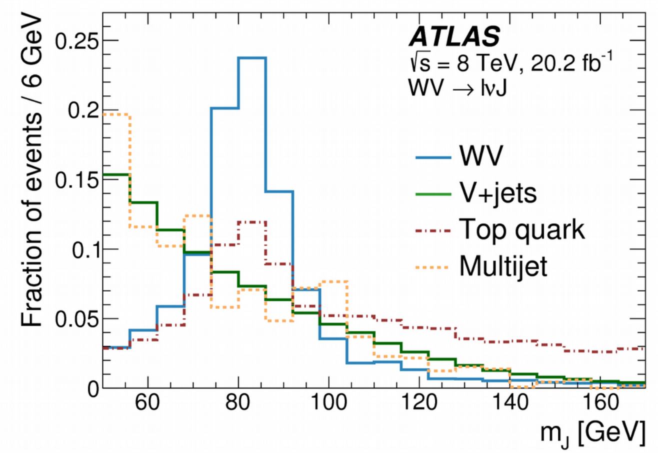
Depending on pT of hadronically-decaying boson, it can be reconstructed as two R=0.4 jets or one with R=1.0. Selection not exclusive!

Resolved channel more statistics, boosted better purity and higher pT

To avoid further statistics losses, no substructure cut applied to boosted

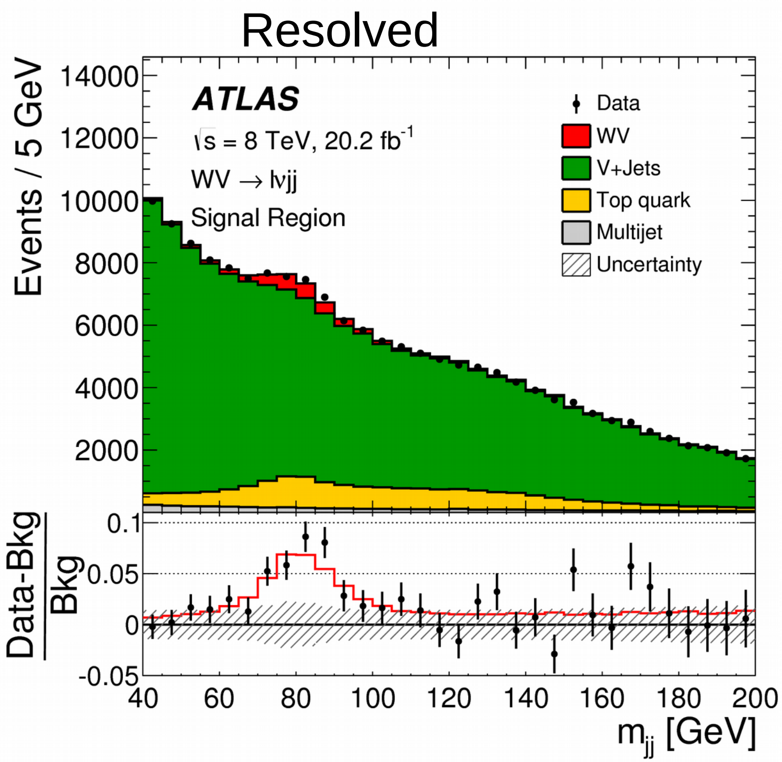


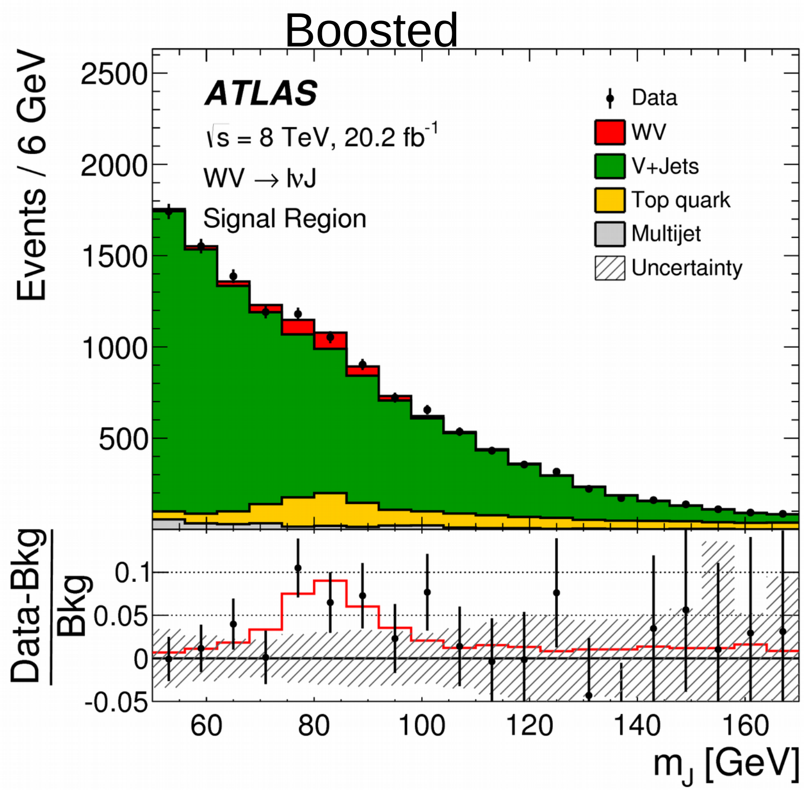




Similar peak resolution between resolved and boosted
→ no way to separate W and Z decays

Semileptonic channel results

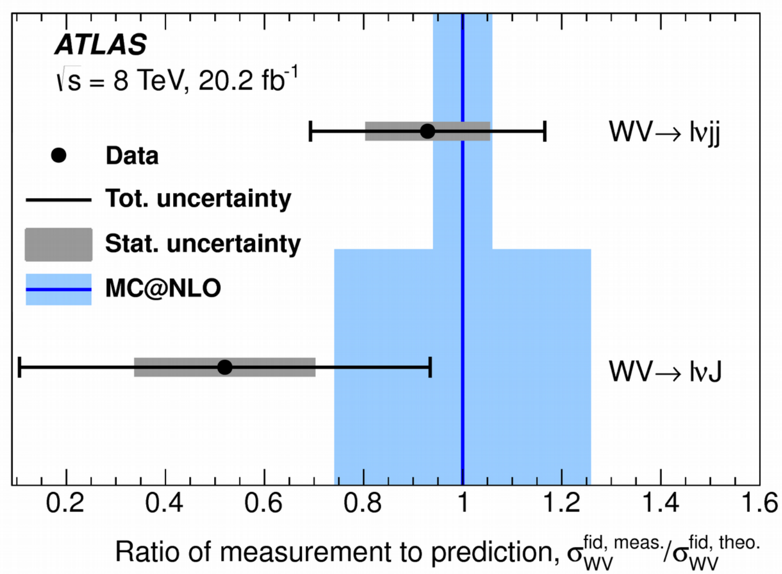




As in leptonic channel, BG from top and V+jets fitted from MC templates, similarly, a slightly lower value than MC expectations is observed

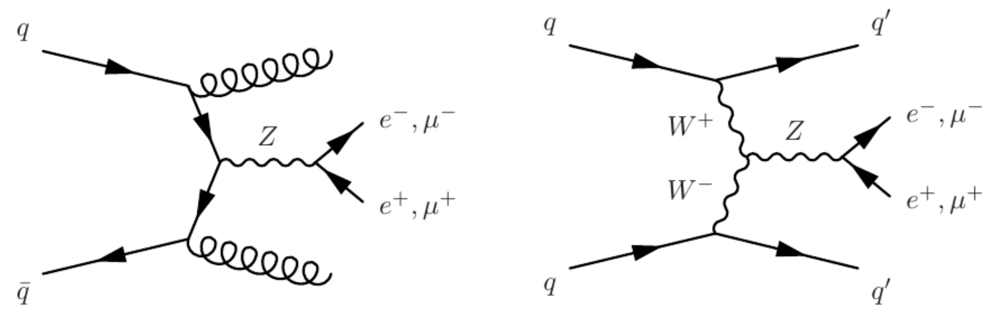
Good agreement with NLO for resolved, under-fluctuation for boosted

Main uncertainties from modeling and large-R scale/resolution



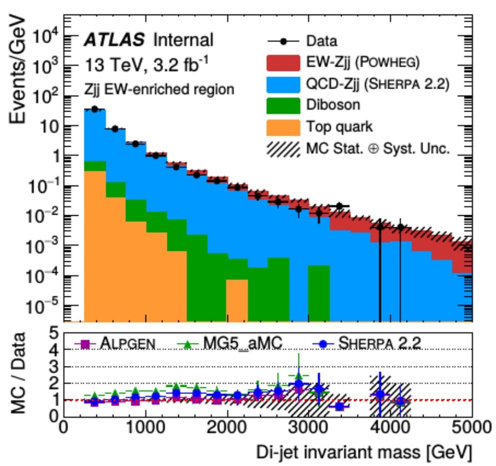
EW Z production (VBF) at 13 TeV

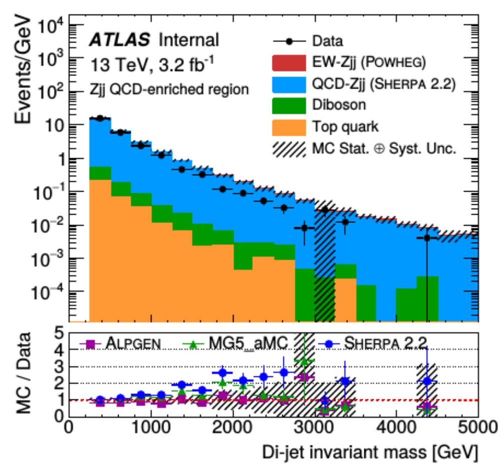
STDM-2016-09, CERN-EP-2017-115
Submitted to Phys Lett B



(a) QCD-Zjj. (b) EW-Zjj.

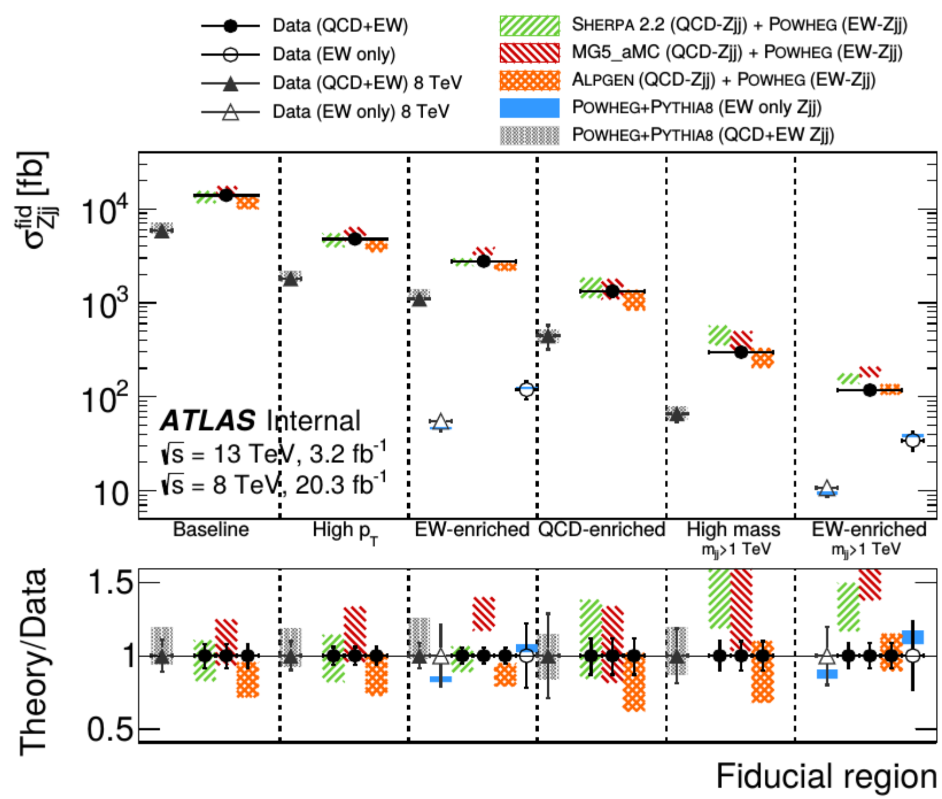
Object	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Di-lepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_T^{j_1} > 55$ GeV		$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV		
Di-jet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N^{\text{interval}}_{\text{jet } (p_T > 25 \text{ GeV})} = 0$		$N^{\text{interval}}_{\text{jet } (p_T > 25 \text{ GeV})} \geq 1$
Zjj system	—			$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance},3} < 0.15$





Measurement performed in 6 fiducial regions to enhance various processes.

EW enriched by high-mass dijets with jet veto, more challenging for theory predictions



Vector Boson Scattering at 8 TeV

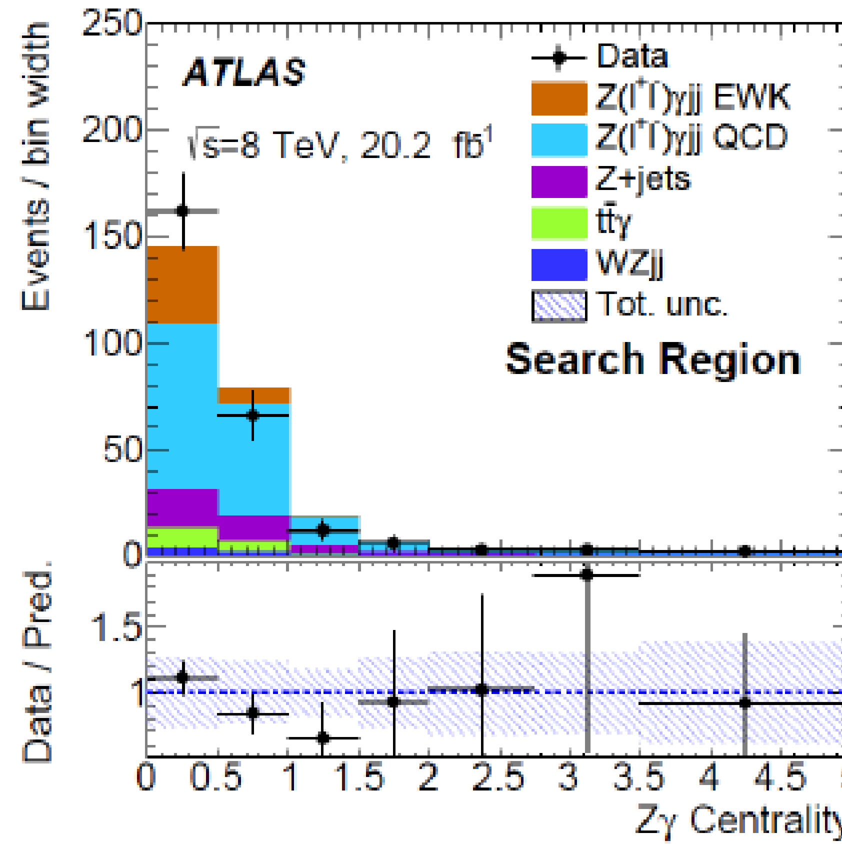
JHEP07(2017)107, ArXiv:1705.01966

Similar to VBF for Higgs production

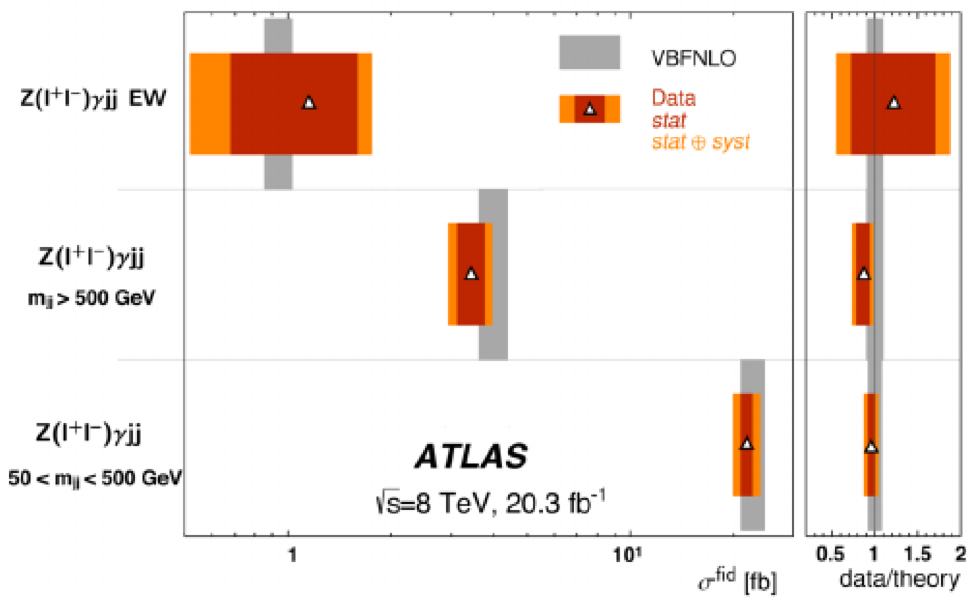
Cross-section stabilised by Higgs diagram

Gamma-Z + 2 (forward) jets with Z in charged lepton or neutrino modes

Separate EW and QCD production using a fit to centrality



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



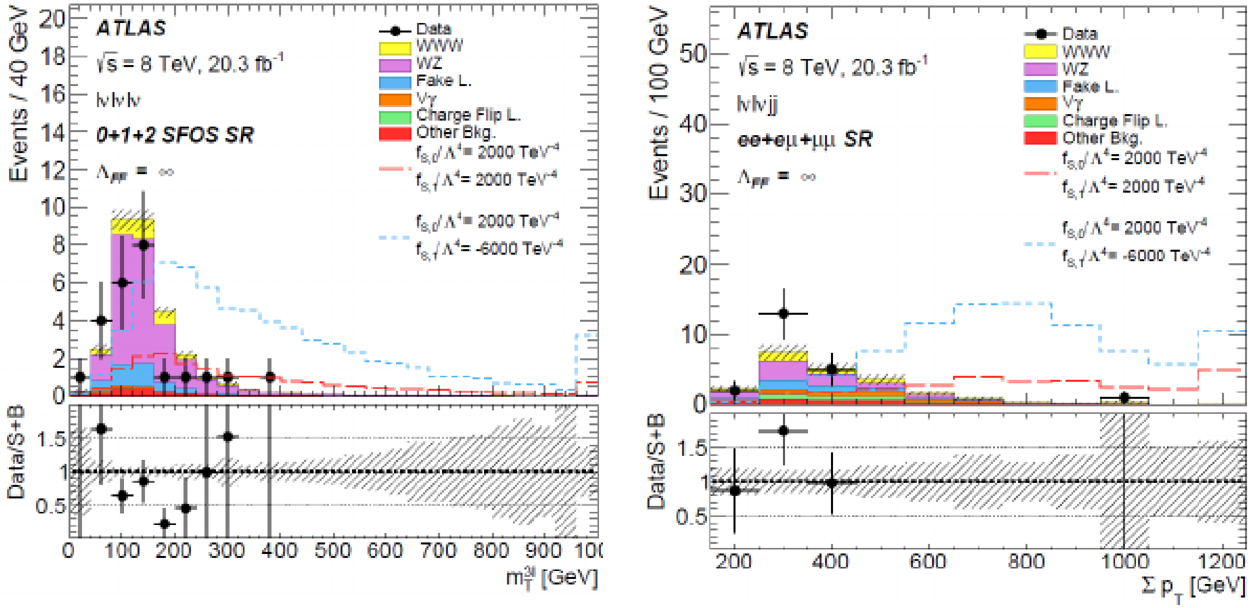
2σ measurement for EW production

WWW production (leptonic and semileptonic: 6 final states)
Eur. Phys. J. C 77 (2017) 141

Full 8 TeV dataset

Very sensitive to quartic couplings

Measurement at 1σ level, still statistics-dominated



		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.)

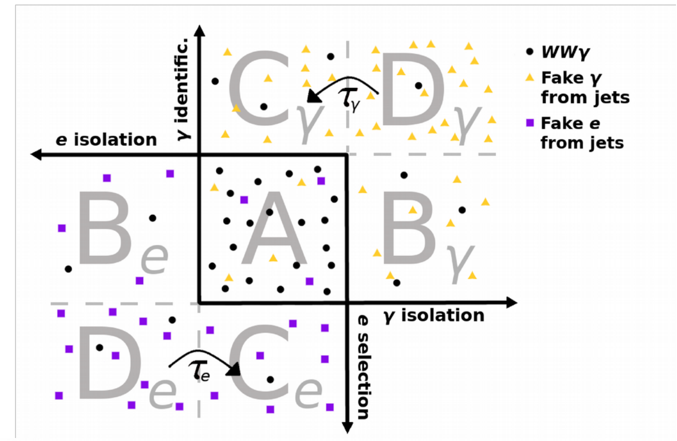
WVγ production at 8 TeV (STDM-2016-05)

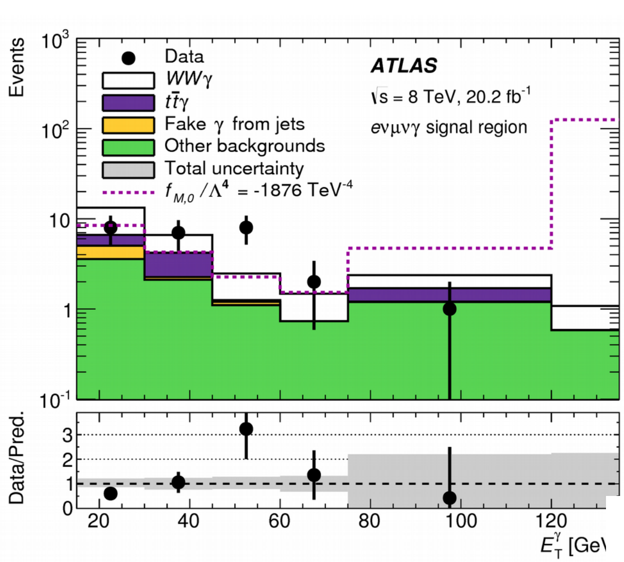
eνμνγ and lνjjγ final states, 1.6σ combined significance

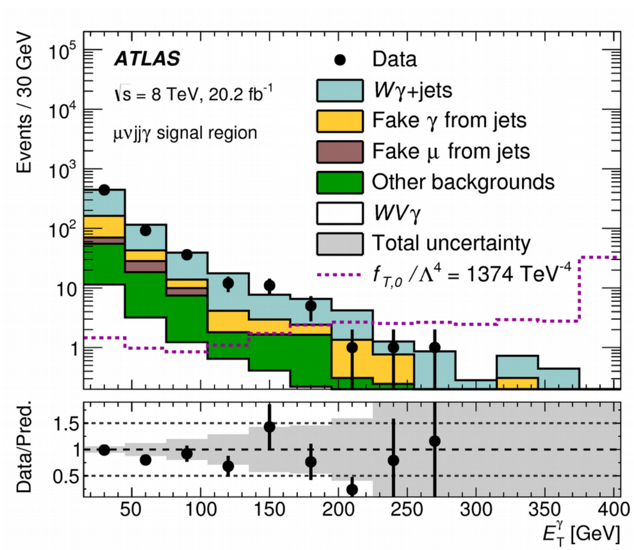
Consistent with to particle-level

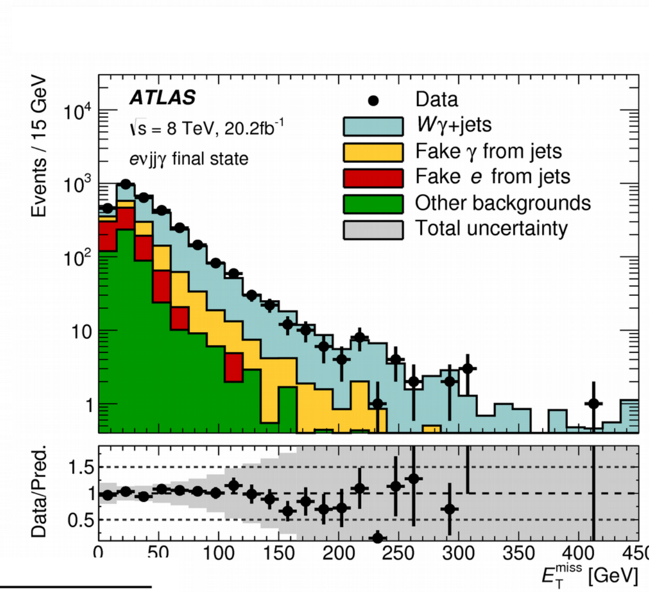
NLO predictions from VBFNLO

BG estimated from multi-dimensional ABCD method



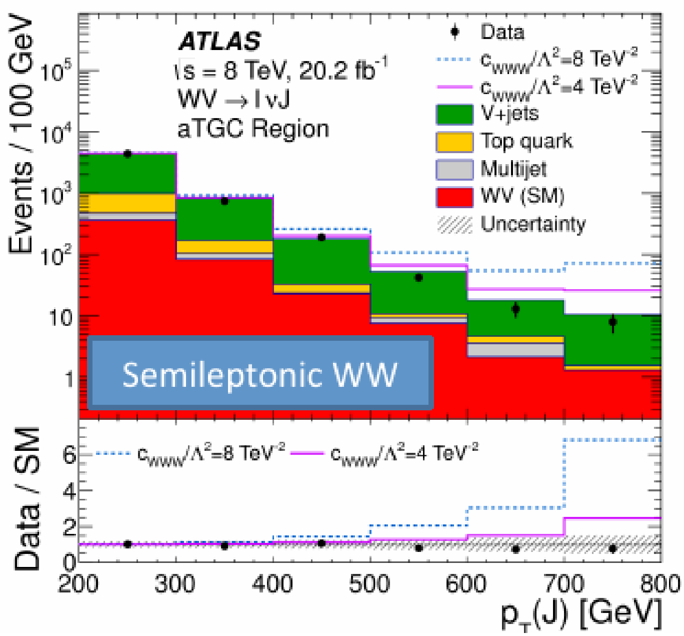


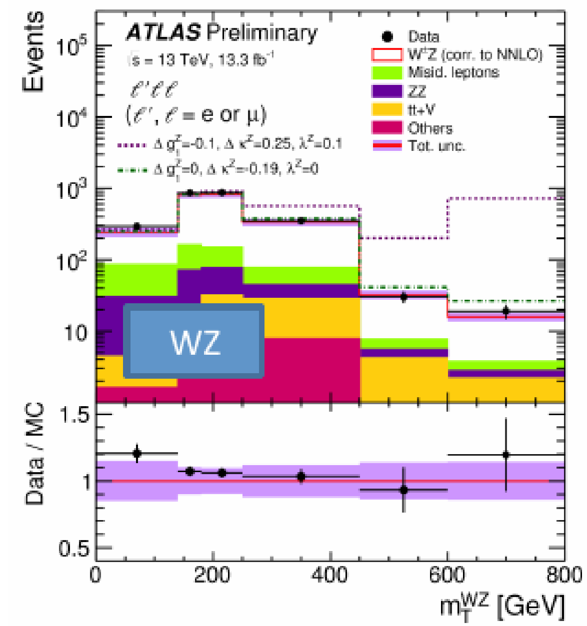


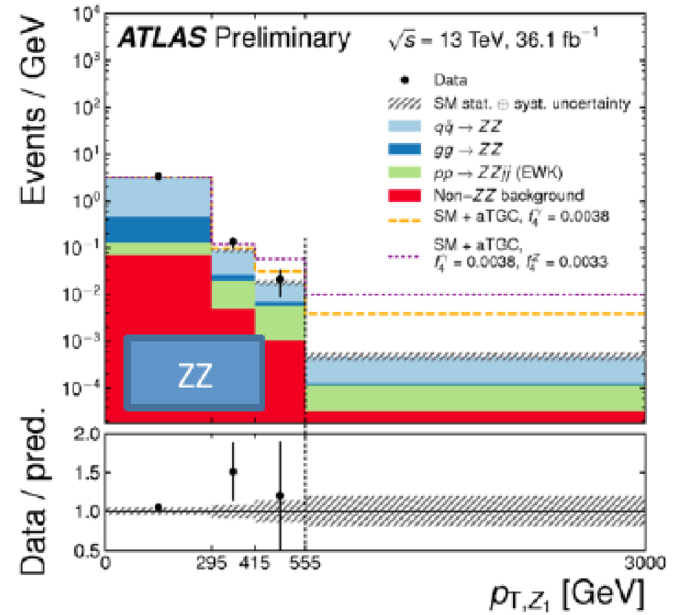


		Observed limit [fb]	Expected limit [fb]	σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0 ± 0.1
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4 ± 0.1
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2 ± 0.1
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3 ± 0.1

Limits to aTGC couplings

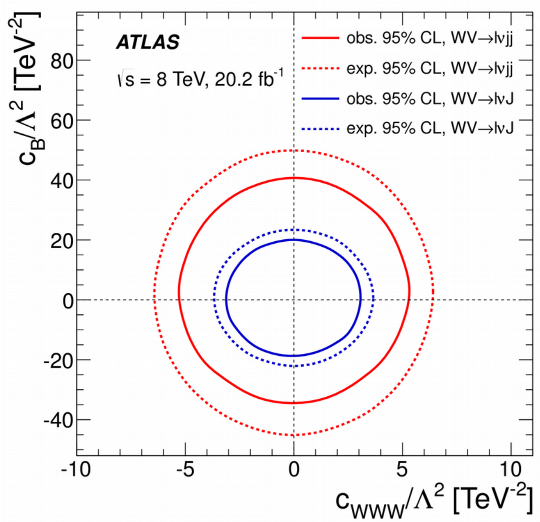


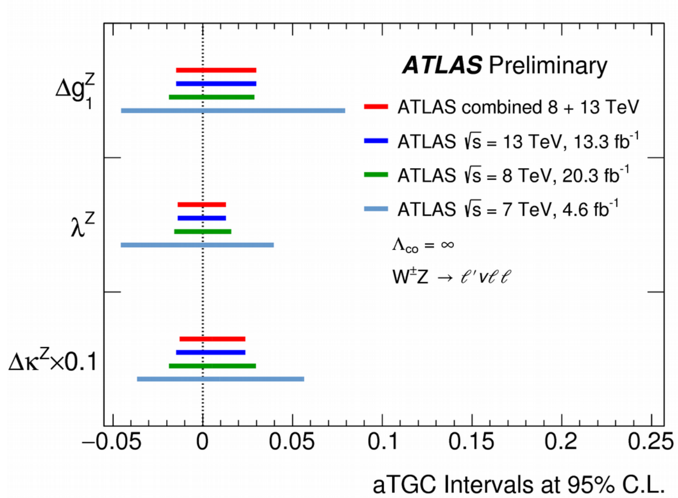


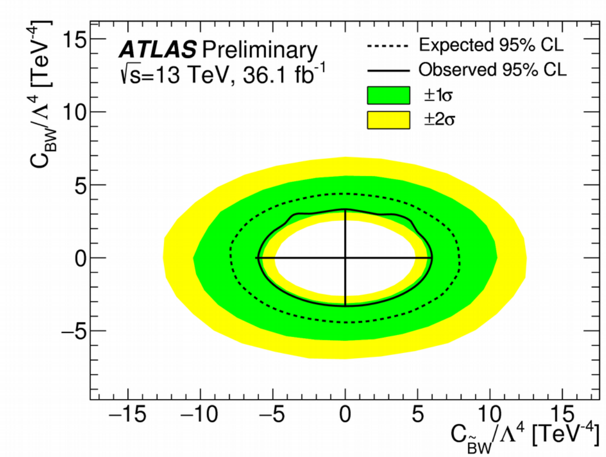


Allowed anomalous values of TGC will lead to deviations at large pT.

Two (equivalent) approaches to parametrisation: adding ad-hoc terms to Lagrangian, or using Effective Field Theory c_{VVV}, c_B



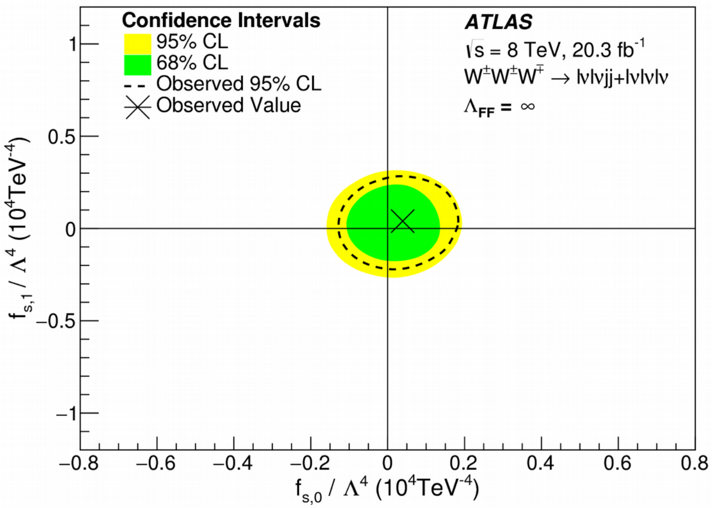




Limits to quartic couplings

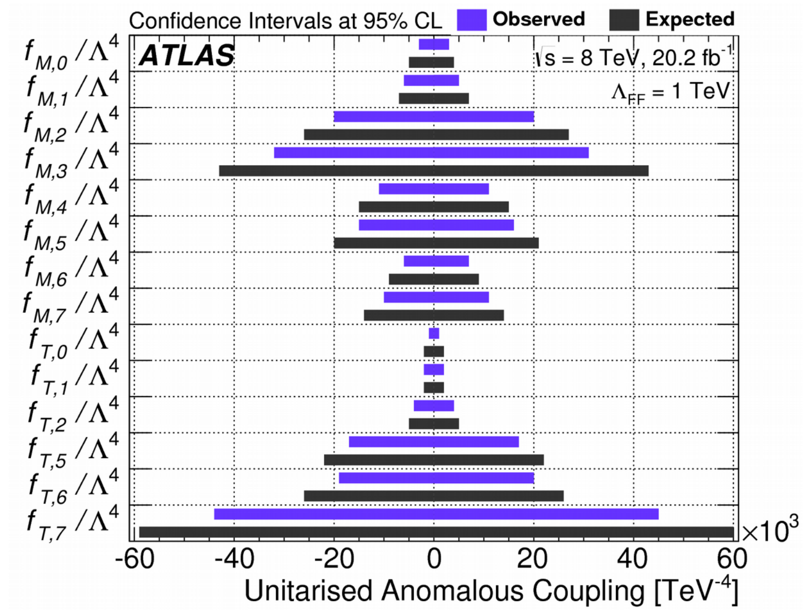
From Z-γ VBS

	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	$[-52, 52]$	$[-43, 43]$



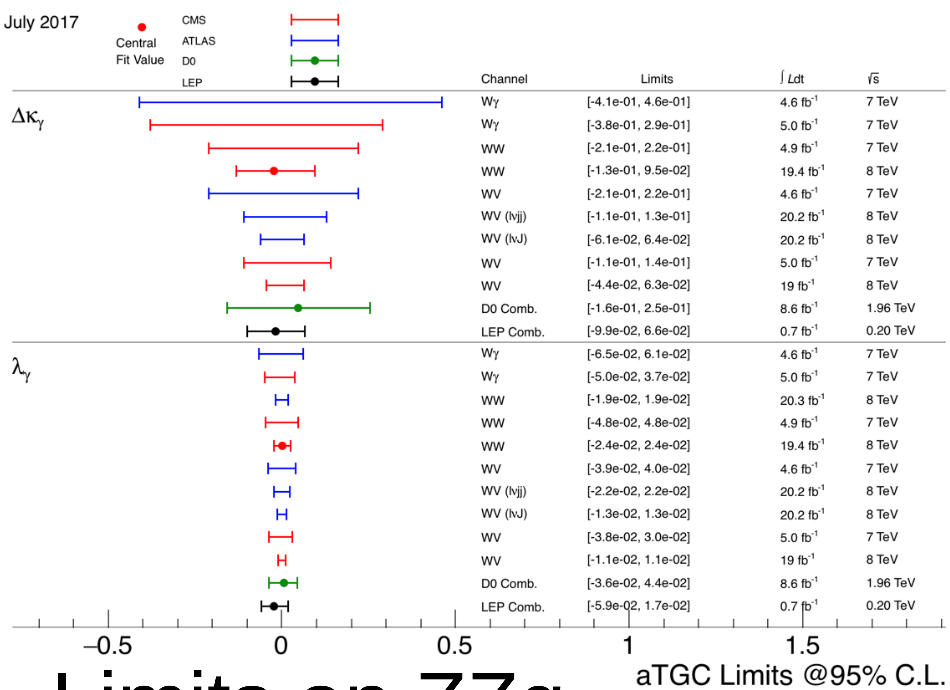
From WVg

From WWW

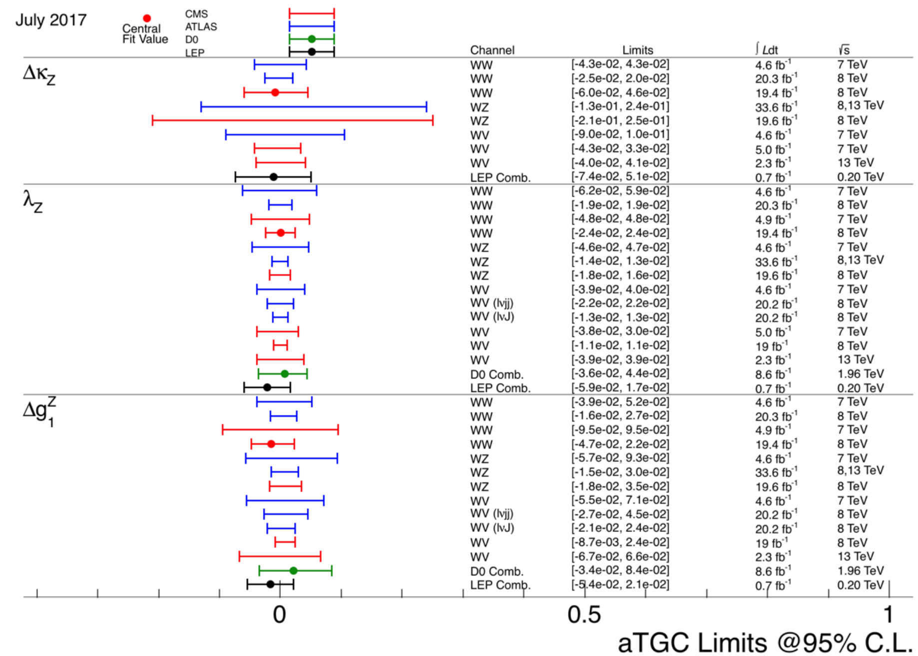


aTGC and aQGC summary

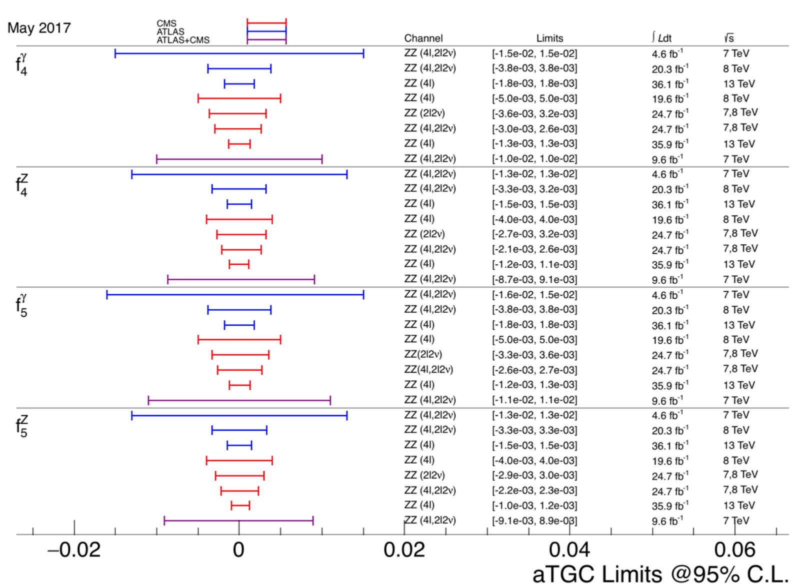
Limits on WWg



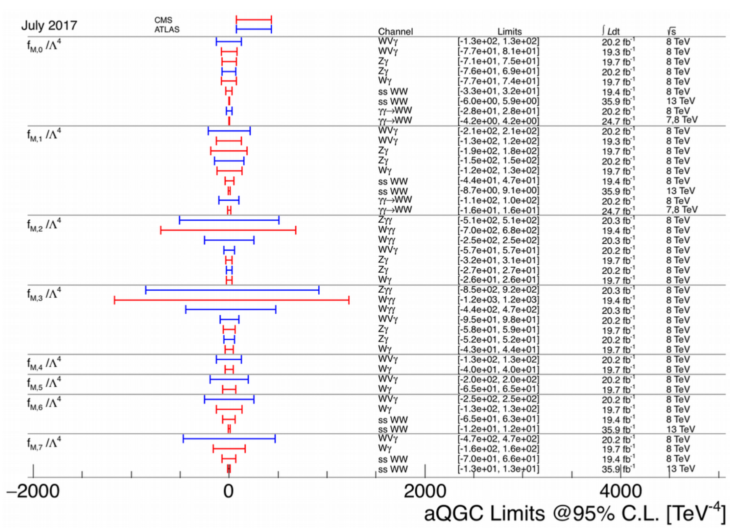
WWZ



Limits on ZZg



Quartic couplings



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

Conclusions

- Dibosons in leptonic final states an established analysis since the beginning of LHC
- Semileptonic final states, especially for boosted bosons, extend kinematic reach
- VBS and tri-boson final states still statistics limited, but already sensitive to quartic couplings (dimension-8 operators in EFT language)
- Anomalous coupling limits already better than those from LEP, a lot of room for further improvements