New tests of the electroweak sector at ATLAS

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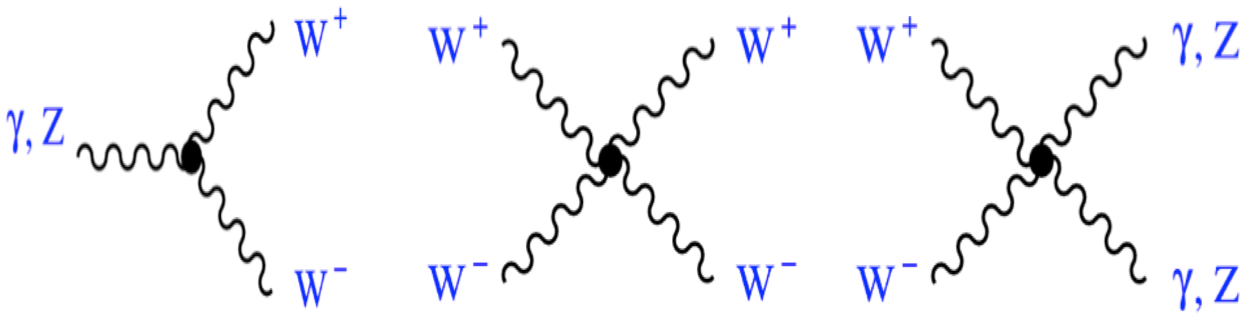
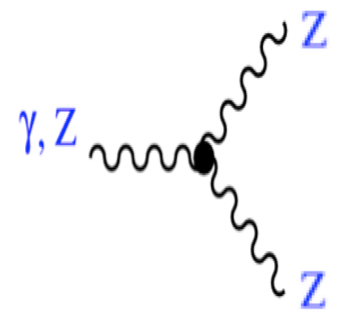
Outline

1) Motivation and experimental considerations
2) Measurement of electroweak Zjj production (a.k.a VBF Z)
3) Measurement of ZZ production
4) Search for WVγ production

Testing the nature of the electroweak interaction



Allowed



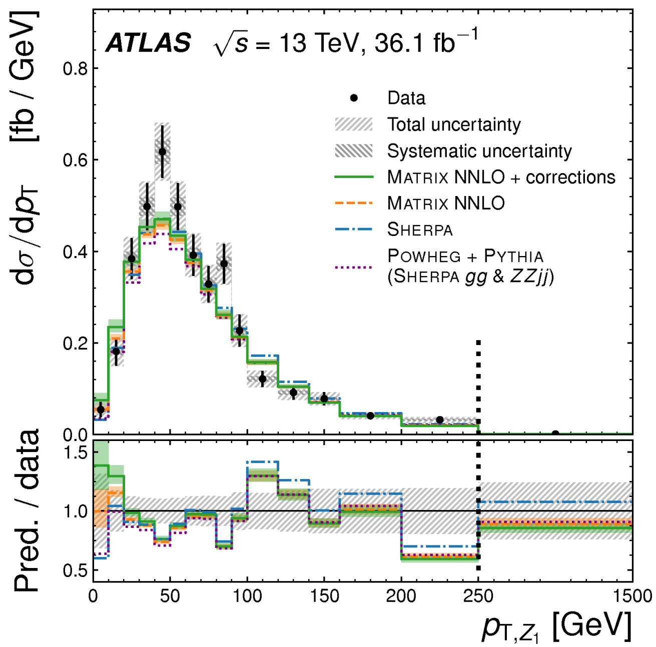
Forbidden

- $SU(2)_L$ x $U(1)_Y$ gauge symmetry of the Standard Model leads to precise predictions for the nature of the electroweak force

- Self interactions of the weak bosons predicted due to non-abelian nature
  - Can be impacted by New Physics at energy scale $\Lambda >> m_W$
  - Important to test the electroweak theory far above the electroweak scale

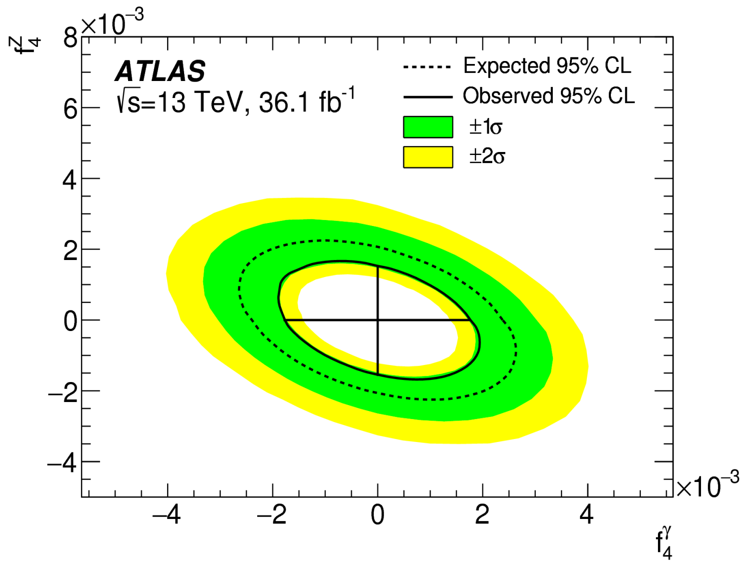
ATLAS approach to quantifying electroweak boson self-couplings

Fiducial/differential cross sections



- Focus on precision measurements of final state kinematics
- Event yields corrected for detector inefficiency and resolution
- Minimal dependence on theoretical modelling

Search for anomalous self-couplings



$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- Easy comparison of sensitivity between experiments
- Results can be easily mapped to specific BSM models

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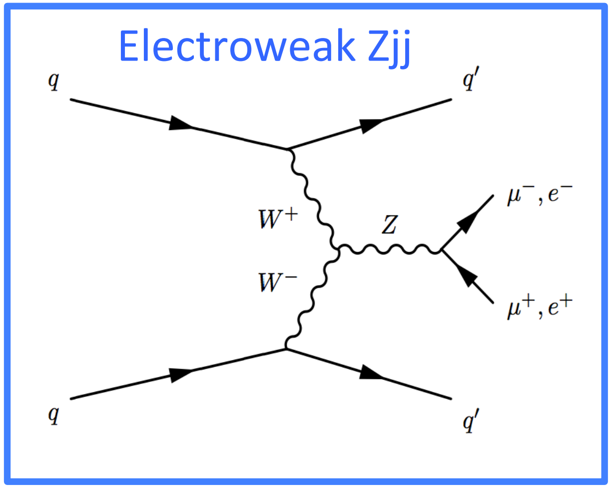
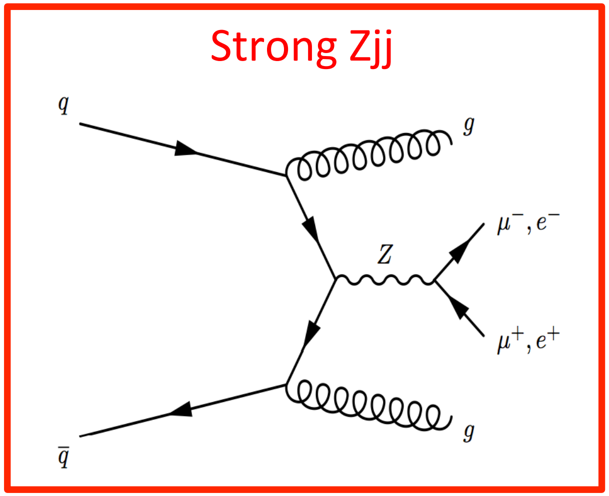
Measurement of electroweak Zjj production at √s=13TeV

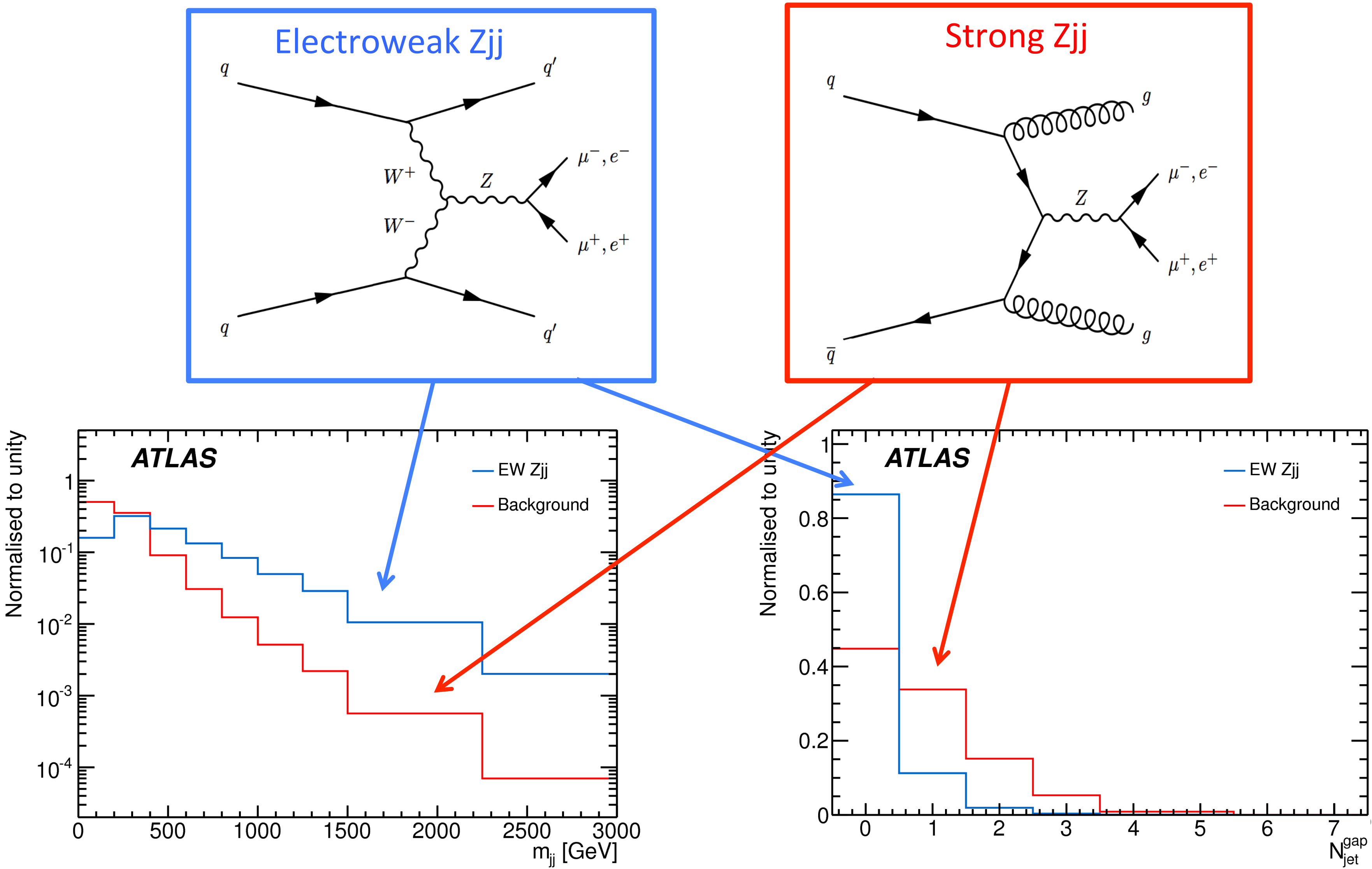




- Weak-boson fusion/scattering plays an important role in Higgs measurements (couplings, ττ) and searches for anomalous gauge couplings.

- Z-production via weak boson fusion is a *standard candle* for these processes
  - In 2014, was the first observation of weak boson fusion at a hadron collider (√s=8TeV)
  - Rare process, just ~1% of the inclusive Zjj cross section

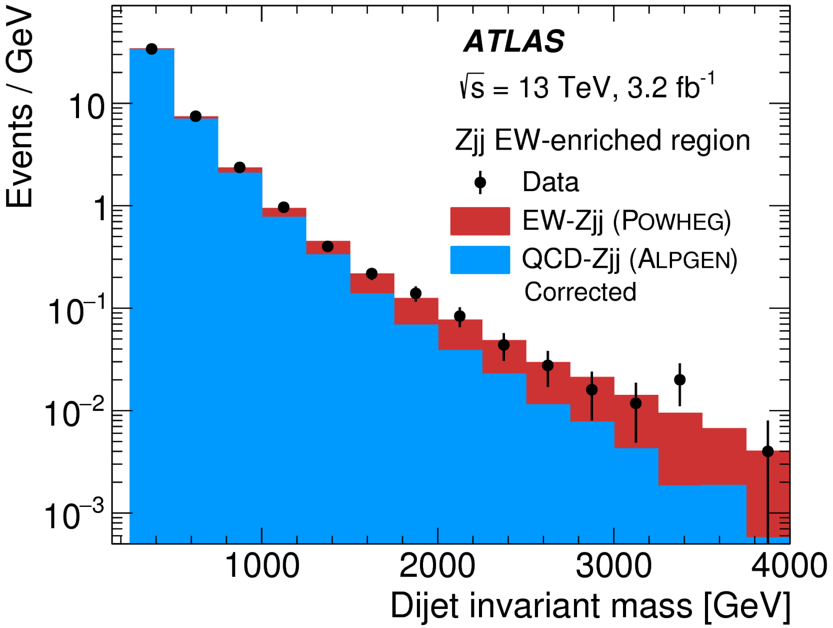
Measurement of electroweak Zjj production at √s=13TeV

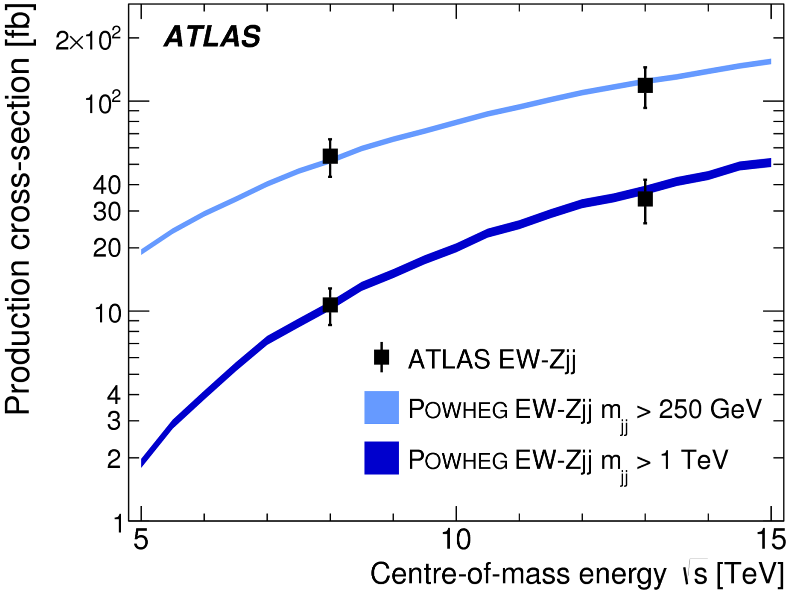


Measured electroweak cross sections

- Signal extracted by a two-template fit to m_{jj} spectrum in an EWK-enriched (search) region, defined (in part) with a veto on additional central-jet activity

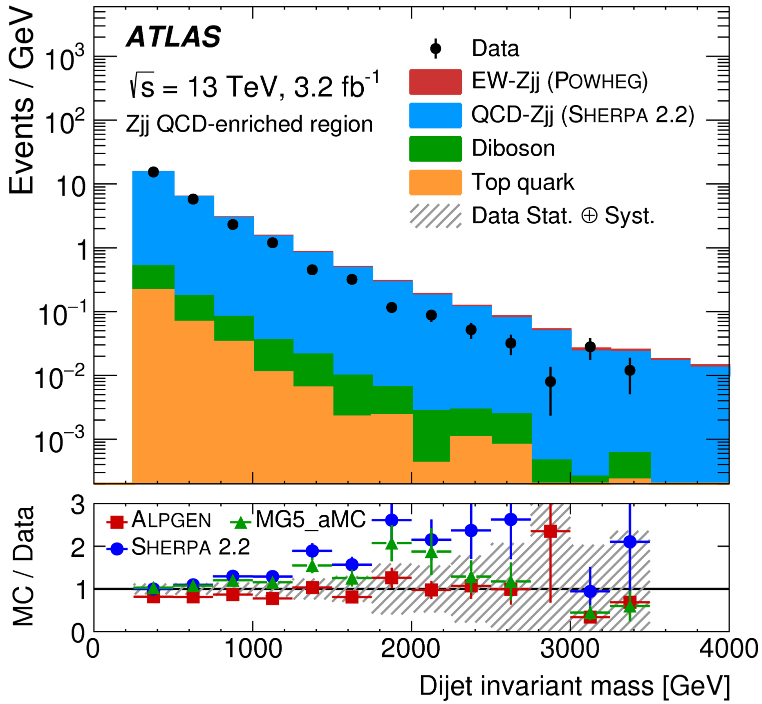
Fiducial region	EW-Zjj cross-sections [fb]	
	Measured	POWHEG+PYTHIA
EW-enriched, $m_{jj} > 250$ GeV	119 $\pm$ 16 $\pm$ 20 $\pm$ 2	125.2 $\pm$ 3.4
EW-enriched, $m_{jj} > 1$ TeV	34.2 $\pm$ 5.8 $\pm$ 5.5 $\pm$ 0.7	38.5 $\pm$ 1.5

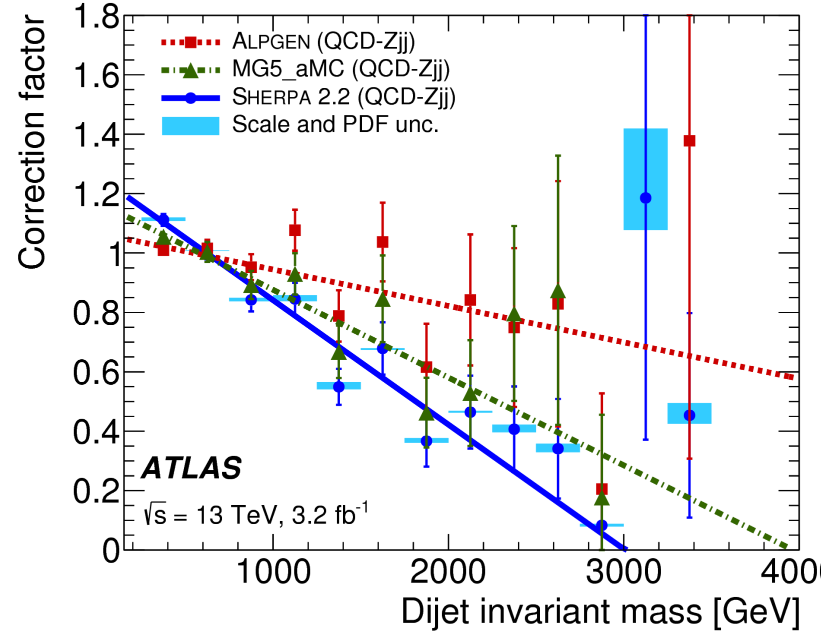




Constraint on strong Zjj background

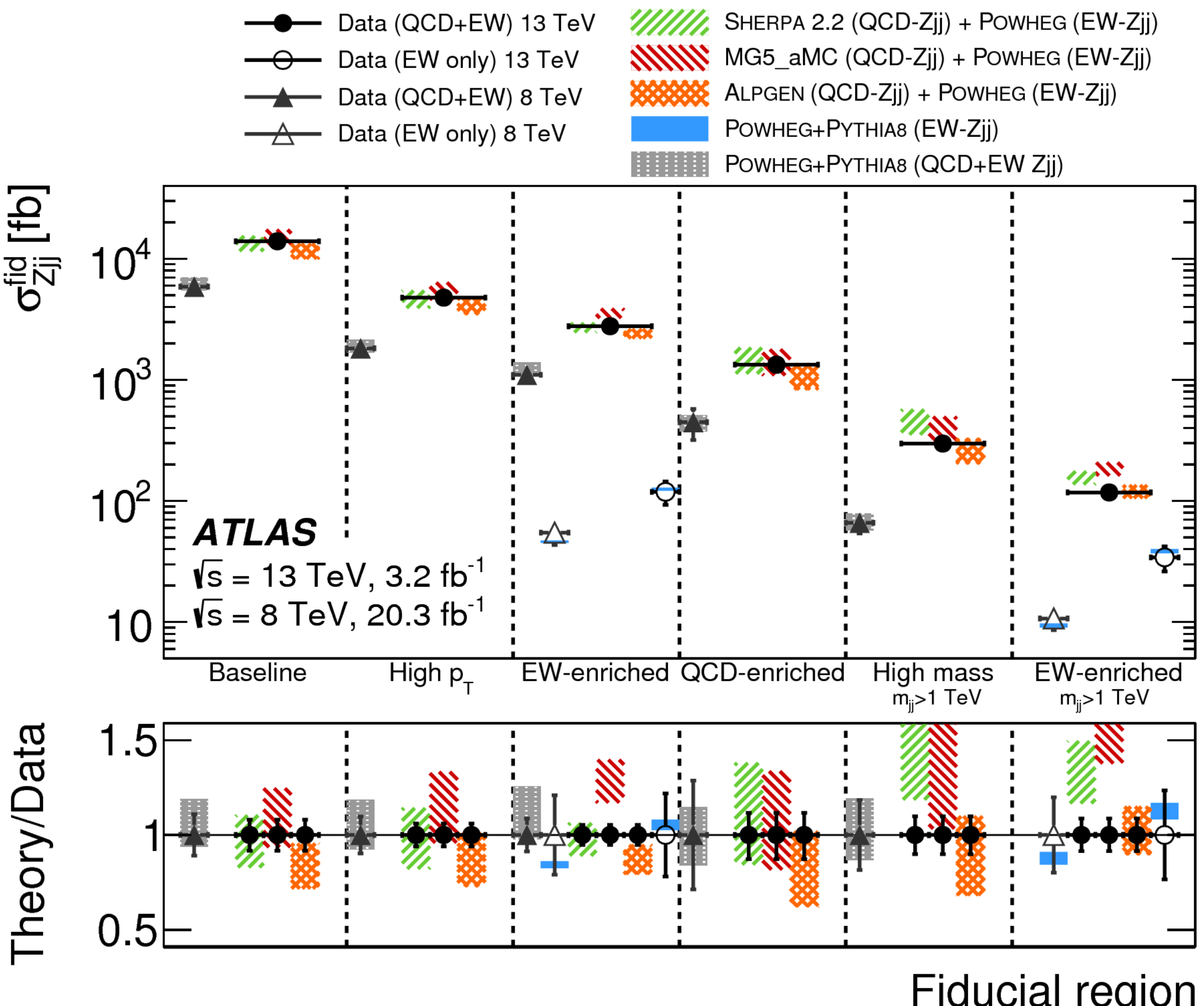
- Background template shape constrained in a EWK-suppressed (control) region, defined by reversing the central jet veto





- Large difference in predictions for different generators, even after using data driven constraint
  - Scale variations for a single generator do not cover this difference (see backup)
  - Limiting factor for future precision measurements

Measured inclusive Zjj cross sections



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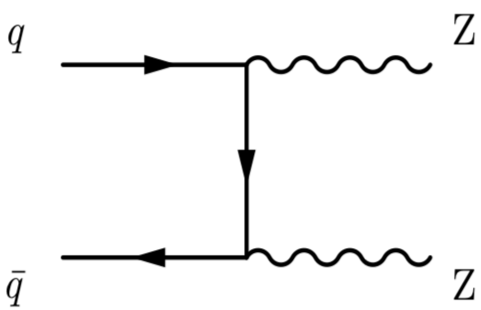
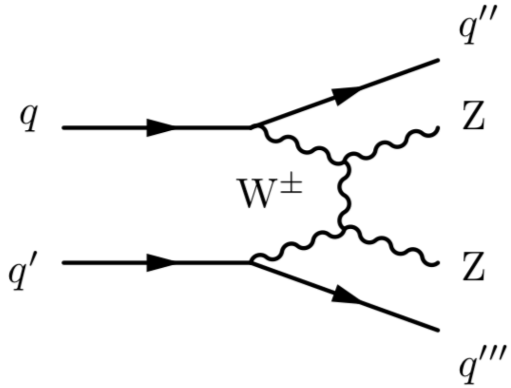
Measurement of ZZ production at √s=13TeV

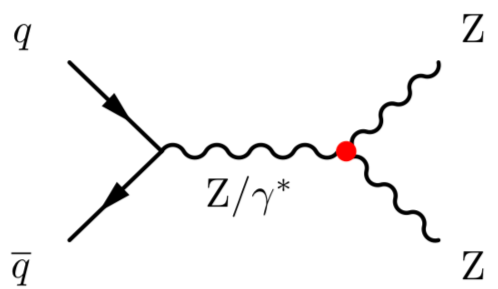
Dominant ZZ mechanism



Electroweak production



Anomalous neutral couplings



- Sensitive to anomalous neutral gauge couplings = forbidden in the SM!
- Major background to H->ZZ* ….. on-shell region relevant for Higgs width
- Very clean, with a reducible background of just 2%.

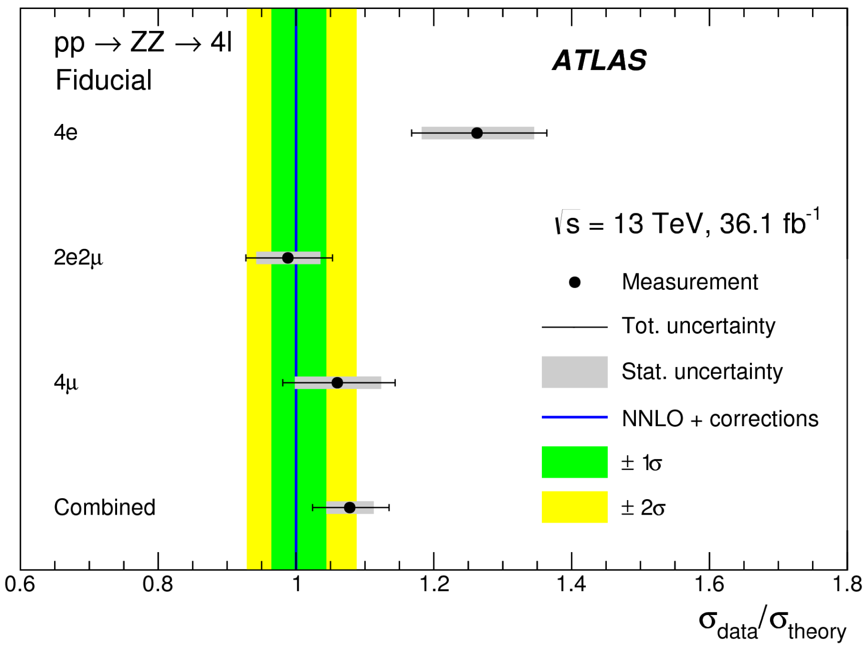
- Increased centre-of-mass energy = increased precision in tails of Z-boson transverse momentum.

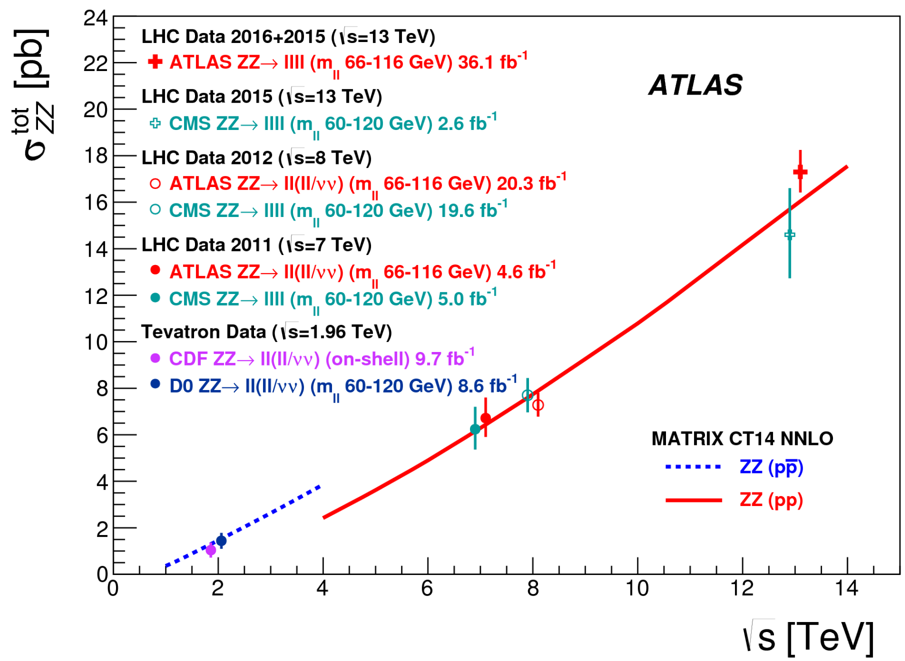
Results: fiducial and total cross sections

Cross-section measured to be 17.3 ± 0.9 pb

- Good agreement with NNLO theory

Two SFOS lepton pairs
Muons (electrons) with $p_T > 5$ (7) GeV
Three leading leptons with p_T>20,15,10 GeV
Quadruplet minimises $|m^a_{\ell\ell} - m_Z| + |m^b_{\ell\ell} - m_Z|$

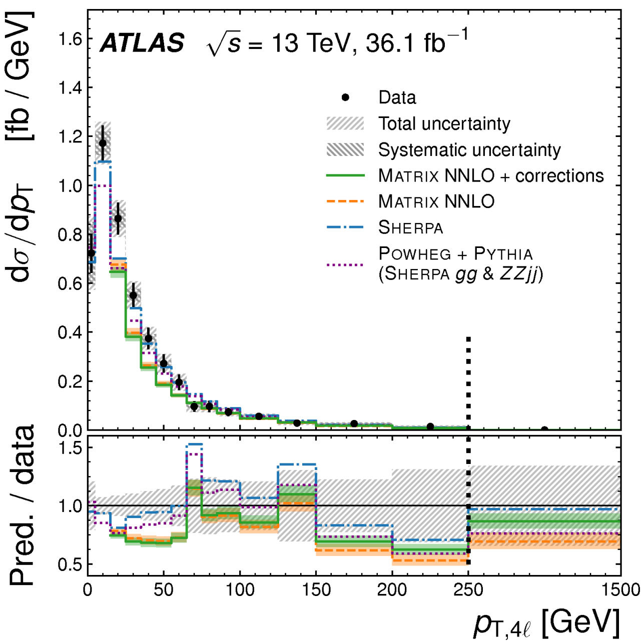




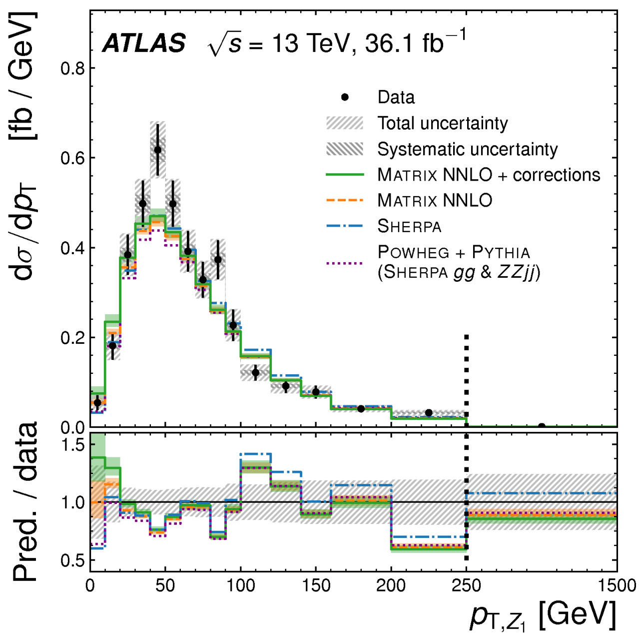
Measurement of differential cross sections

- Differential cross sections measured as a function of Z-boson, lepton and jet kinematic quantities
- Unfolded using D'Agostini's method (iterative, based on Bayes theorem)

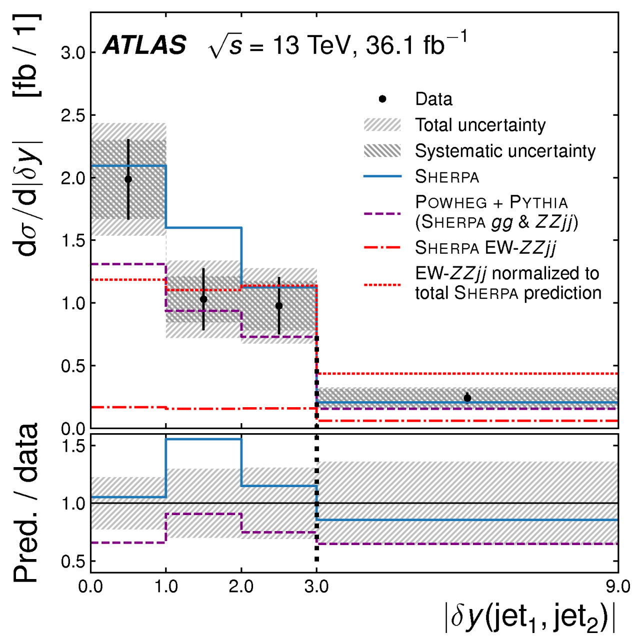
Sensitive to QCD modelling



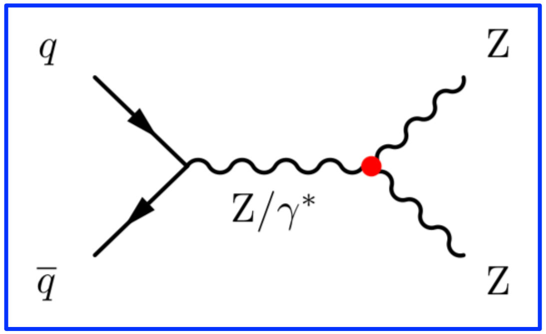
Sensitive to aNGC



Sensitive to EWK ZZjj

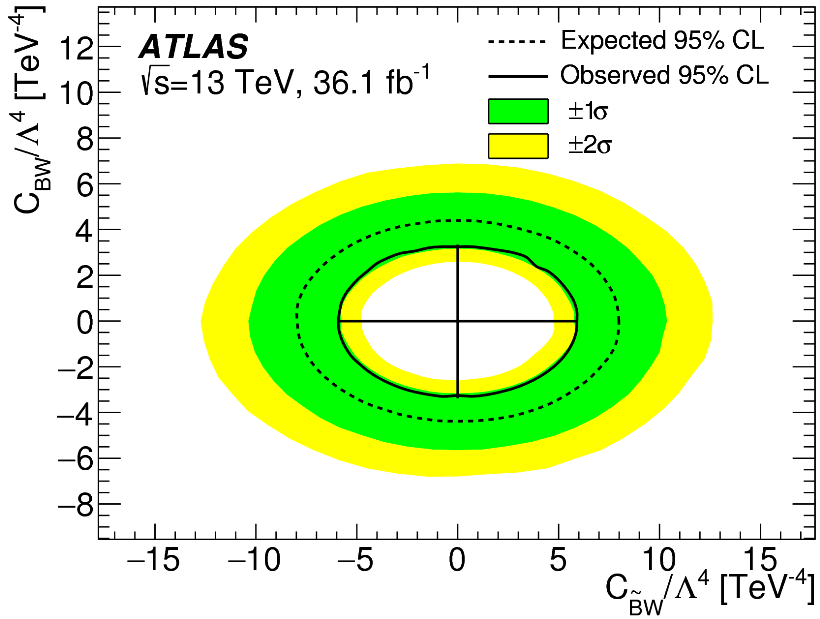


Constraints on anomalous neutral gauge couplings



$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

EFT basis in: JHEP 1402 (2014) 101



EFT parameter	Expected 95% CL $[\text{TeV}^{-4}]$	Observed 95% CL $[\text{TeV}^{-4}]$
$C_{\tilde{B}W}/\Lambda^4$	$-8.1, 8.1$	-5.9 , 5.9
C_{WW}/Λ^4	$-4.0, 4.0$	-3.0 , 3.0
C_{BW}/Λ^4	$-4.4, 4.4$	-3.3 , 3.3
C_{BB}/Λ^4	$-3.7, 3.7$	-2.7 , 2.8

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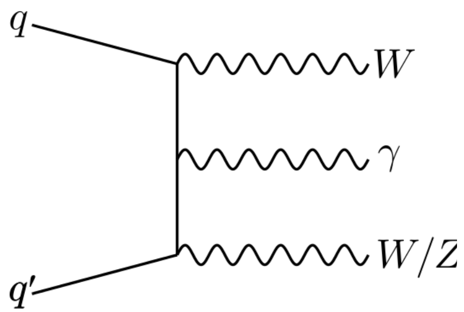
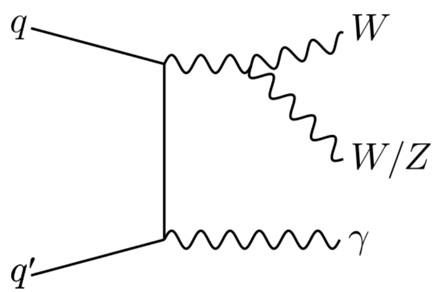
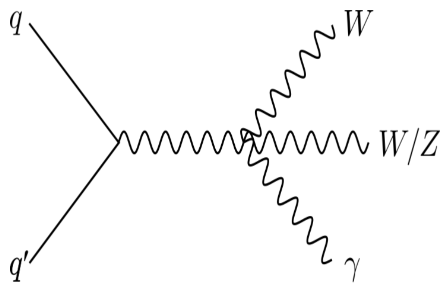
Measurement of WVγ production at √s=8TeV

Radiative production of weak bosons





Quartic gauge couplings



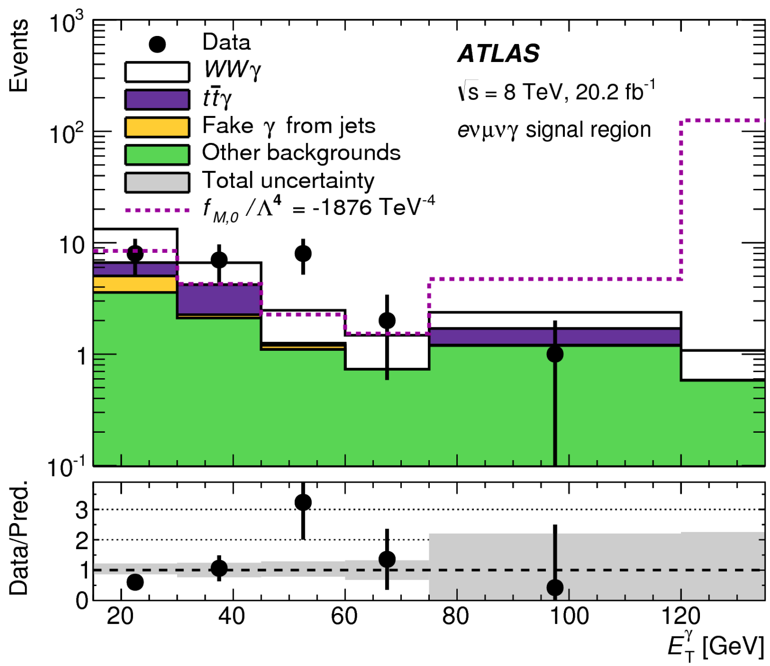
- Direct test for quartic gauge couplings predicted by electroweak theory
- Sensitive to BSM physics, characterised by dimension-8 effective Lagrangian:

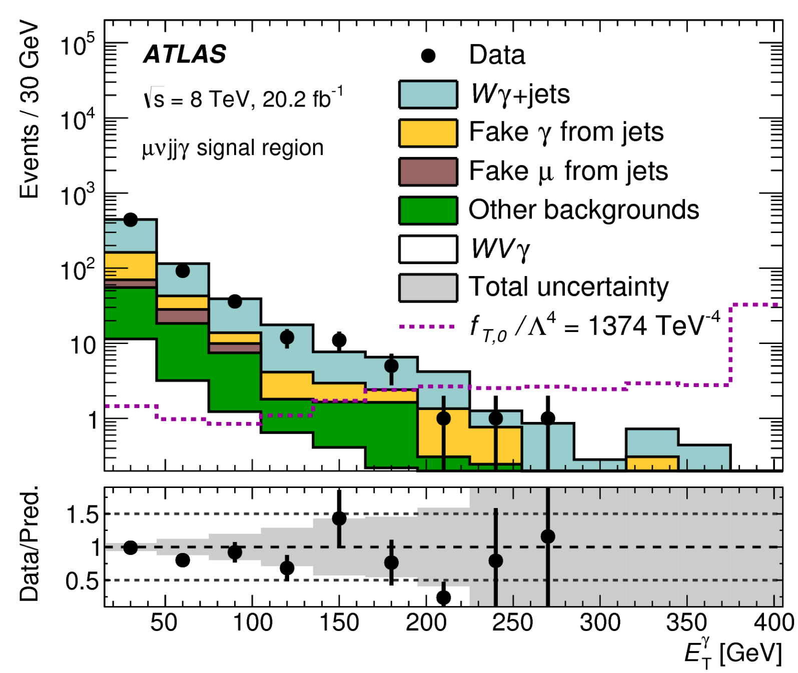
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{j=0}^{7} \frac{f_{M,j}}{\Lambda^4} O_{M,j} + \sum_{j=0,1,2,5,6,7} \frac{f_{T,j}}{\Lambda^4} O_{T,j},$$

- Two analysis strategies:
  - WWγ analysis in fully-leptonic decay of the two W boson
  - WVγ analysis with hadronic decay of the V-boson

Upper limits on production cross section

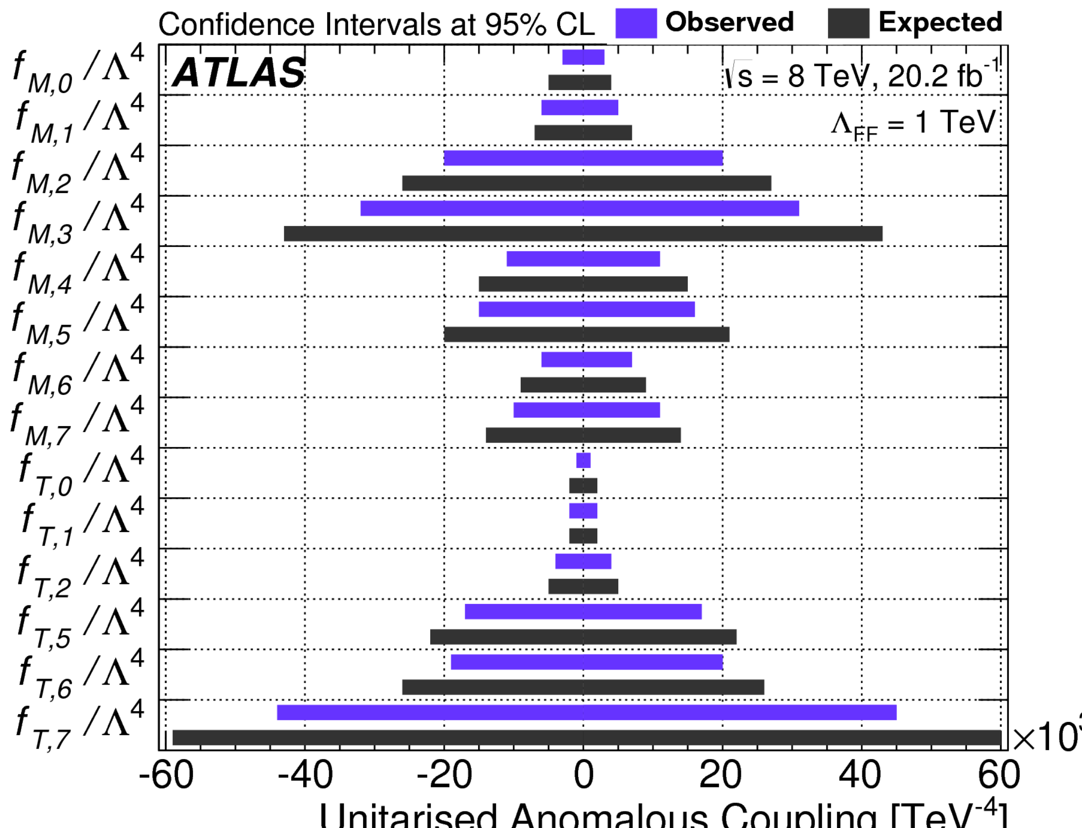
		Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0 ± 0.1
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4 ± 0.1
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2 ± 0.1
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3 ± 0.1





Constraints on anomalous quartic gauge couplings

	E_{T}^{γ} threshold [GeV]	N_{obs}	N_{bg}	ϵ	C^{p2p}
$e\nu\mu\nu\gamma$	120	0	$0.1^{+0.2}_{-0.1}$	0.3 ± 0.1	1.1 ± 0.1
$e\nu jj\gamma$	200	4	6 ± 6	0.4 ± 0.1	0.6 ± 0.2
$\mu\nu jj\gamma$	200	3	4^{+12}_{-4}	0.4 ± 0.1	0.6 ± 0.1



Summary and prospects

Electroweak Zjj production

- Fiducial cross section measurement at $\sqrt{s}$=13TeV with 3.2fb^{-1} of data.
- Full Run-II analysis will benefit from nearly 50x data! = first differential cross sections
- Better modelling on strong Zjj production will be crucial

ZZ production

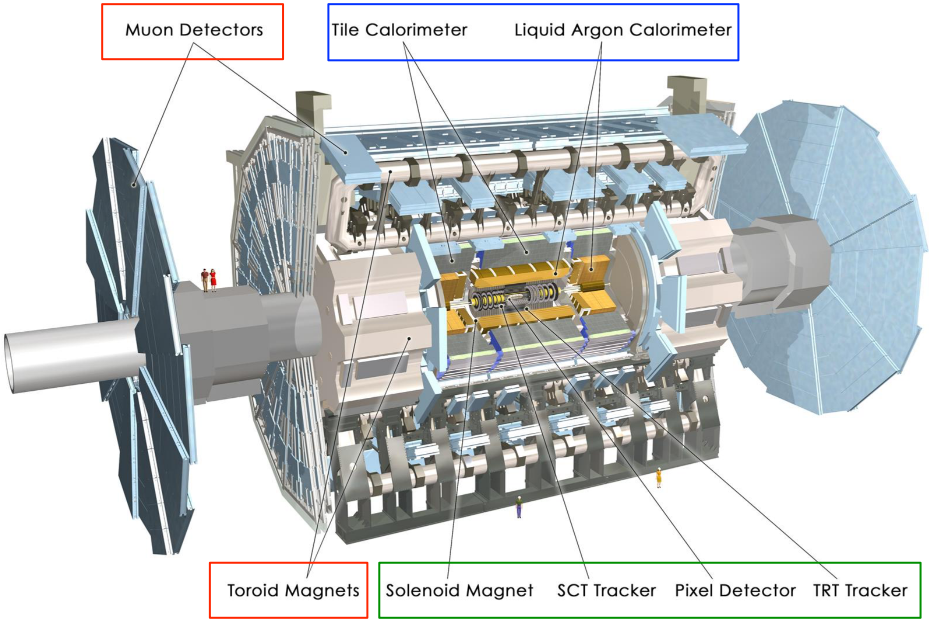
- Fiducial and differential cross section measurements at $\sqrt{s}$=13TeV with 36fb^{-1} of data
- Excellent constraints on anomalous neutral gauge couplings

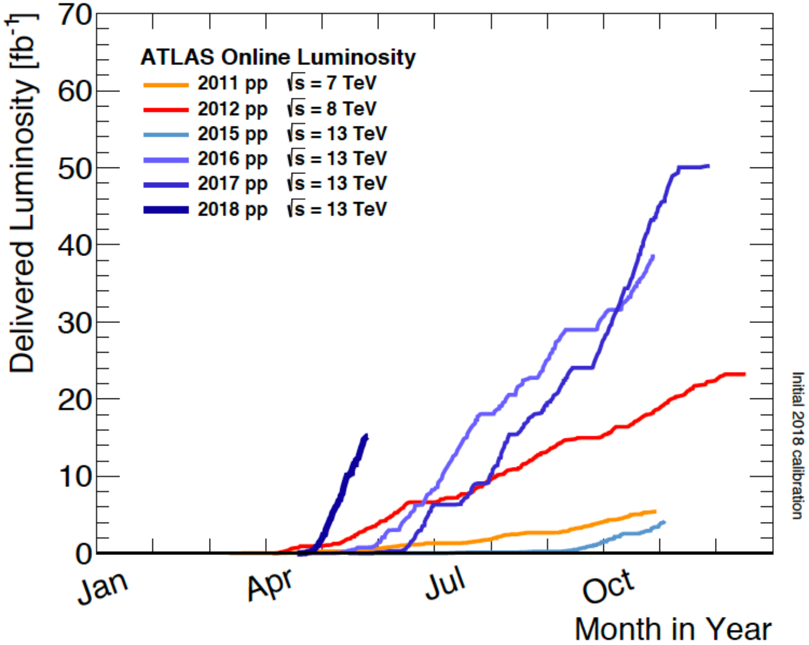
WVγ production

- Searches at $\sqrt{s}$=8TeV with 30fb^{-1} of data
- Fully-leptonic WWγ measurement significance of 1.6σ = expect evidence with full Run-II
- Upper limits on semi-leptonic WVγ production

Backup

Experimental considerations





- Jets with |η|<4.5 (Calorimeters)
- e, γ with |η|<2.5 (Calorimeters + Inner detector)
- muons with |η|<2.7 (Muon spectrometer + ID)
- Missing transverse momentum

- Higher centre-of-mass energy:
  - Increased sensitivity to tails of differential distributions
  - Increased sensitivity to large partonic centre-of-mass (e.g VBF/VBS)

Selection in five fiducial regions: different sensitivity to electroweak Zjj

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j1} > 55$ GeV				$p_T^{j1} > 85$ GeV
	$p_T^{j2} > 45$ GeV				$p_T^{j2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}} = 0$	$N_{\text{jet}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance,3}} < 0.15$	—

--- Z-boson selection

--- Baseline jet selection

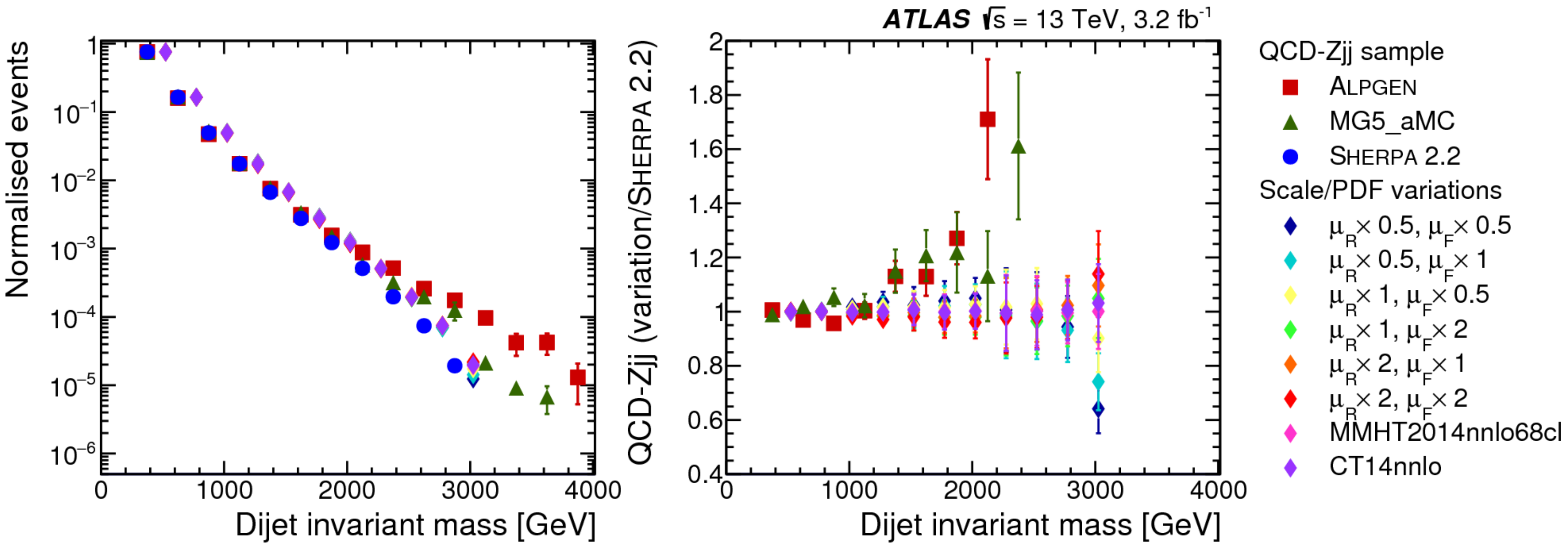
--- Probe of high-p_T or high-mass

--- Search/control cuts for electroweak extraction

Systematic uncertainties in VBF Zjj measurement

Source	Relative systematic uncertainty [%] $\sigma_{\mathrm{EW}}^{m_{jj}>250\ \mathrm{GeV}}$	$\sigma_{\mathrm{EW}}^{m_{jj}>1\ \mathrm{TeV}}$
EW-*Zjj* signal modelling (QCD scales, PDF and UEPS)	± 7.4	± 1.7
EW-*Zjj* template statistical uncertainty	± 0.5	± 0.04
EW-*Zjj* contamination in QCD-enriched region	–0.1	–0.2
QCD-*Zjj* modelling (m_{jj} shape constraint / third-jet veto)	± 11	± 11
Stat. uncertainty in QCD control region constraint	± 6.2	± 6.4
QCD-*Zjj* signal modelling (QCD scales, PDF and UEPS)	± 4.5	± 6.5
QCD-*Zjj* template statistical uncertainty	± 2.5	± 3.5
QCD–EW interference	± 1.3	± 1.5
$\bar{t}t$ and single-top background modelling	± 1.0	± 1.2
Diboson background modelling	± 0.1	± 0.1
Jet energy resolution	± 2.3	± 1.1
Jet energy scale	+5.3/–4.1	+3.5/–4.2
Lepton identification, momentum scale, trigger, pile-up	+1.3/–2.5	+3.2/–1.5
Luminosity	± 2.1	± 2.1
Total	± 17	± 16

Theoretical modelling issues for the strong Zjj background



- Large difference in predictions for different generators, even after using the data driven constraint
  - Scale variations for a single generator do not cover this difference.
  - Limiting factor for future precision measurements

Selection of ZZ events

Type	**Input or requirement**
Leptons (e, μ)	Prompt Dressed with prompt photons within $\Delta R = 0.1$ (added to closest prompt lepton) $p_{\mathrm{T}} > 5\ GeV$ $\lvert\eta\rvert < 2.7$
Quadruplets	Two same-flavor opposite-charge lepton pairs Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV
Events	Only quadruplet minimizing $\lvert m^a_{\ell\ell} - m_Z\rvert + \lvert m^b_{\ell\ell} - m_Z\rvert$ is considered Any same-flavor opposite-charge dilepton has mass $m_{\ell\ell} > 5$ GeV $\Delta R > 0.1$ (0.2) between all same-flavor (different-flavor) leptons Dileptons minimizing $\lvert m^a_{\ell\ell} - m_Z\rvert + \lvert m^b_{\ell\ell} - m_Z\rvert$ are taken as Z boson candidates Z boson candidates have mass $66\ GeV < m_{\ell\ell} < 116$ GeV
Jets	Clustered from all non-prompt particles Anti-k_t algorithm with $R = 0.4$ $p_{\mathrm{T}} > 30\ GeV$ $\lvert\eta\rvert < 4.5$ Rejected if within $\Delta R = 0.4$ of a fiducial lepton