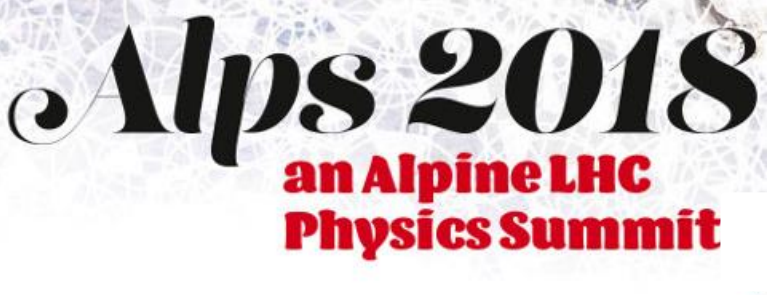

Tests of the electroweak sector with Z boson at the ATLAS experiment

1. Electroweak Z+2jj measurement at 13 TeV.
2. ZZ production at 13 TeV.

Jonathan Crane

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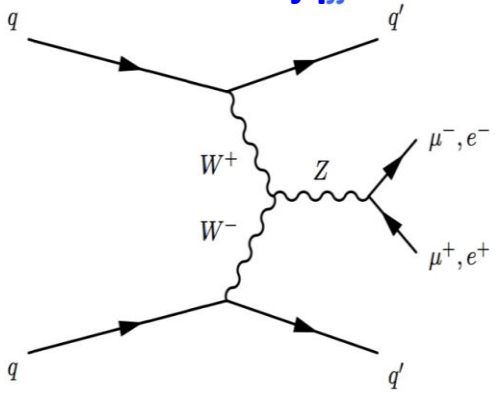
On behalf of the ATLAS collaboration

Introduction

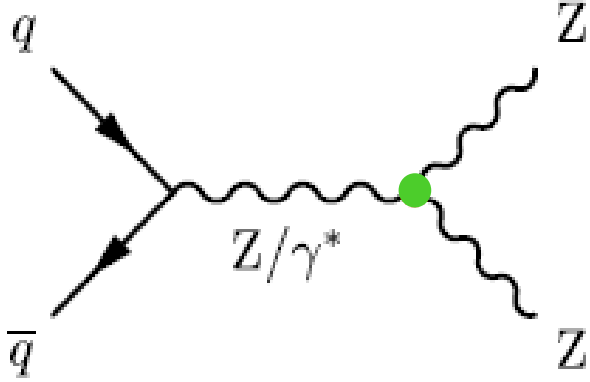
This talk focuses on two analyses that use the ATLAS Run-2 data that probe self-interactions of the weak bosons:

- The electroweak production of di-jets in association with a Z boson.
  - https://www.sciencedirect.com/science/article/pii/S0370269317308523
  - Probe momentum scales far above the electroweak scale.
- The measurement of ZZ production.
  - https://journals.aps.org/prd/abstract/10.1103/PhysRevD.97.032005
  - Search for anomalous triple gauge couplings (aTGCs).

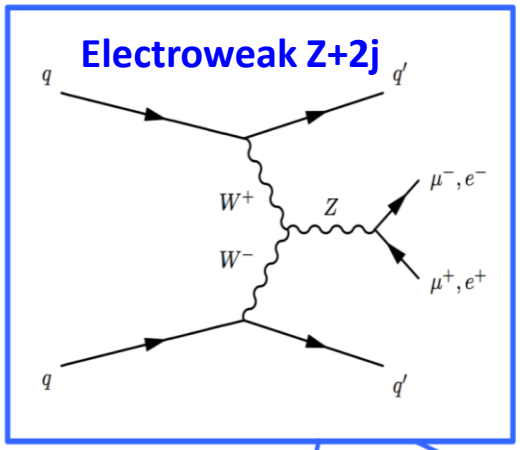
Electroweak Z+2j production

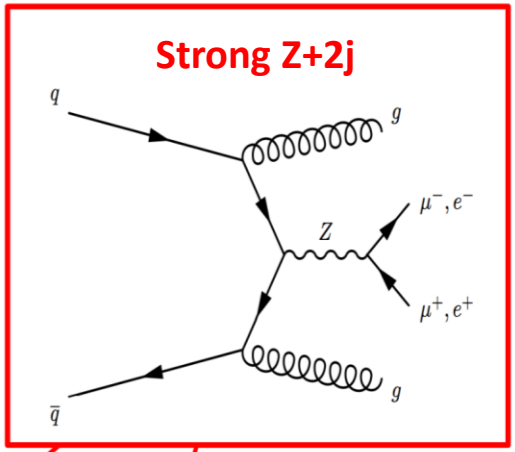


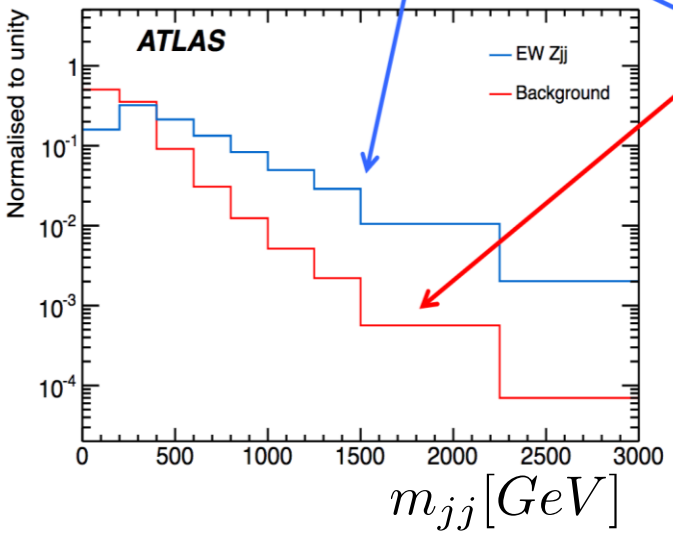
ZZ production with aTGC

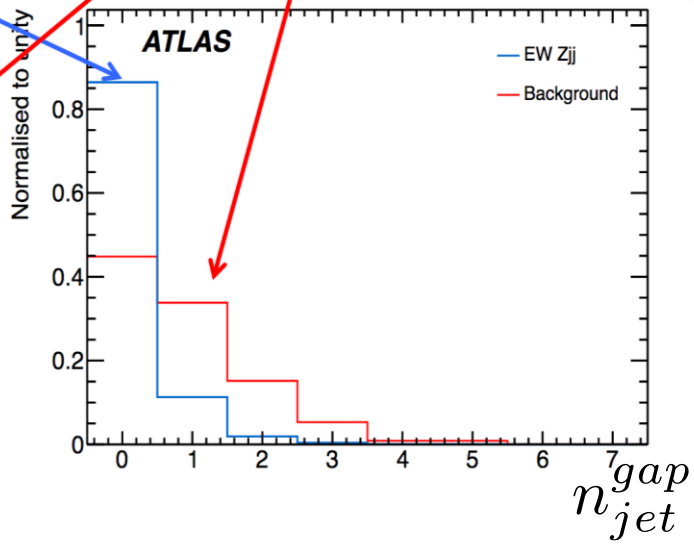


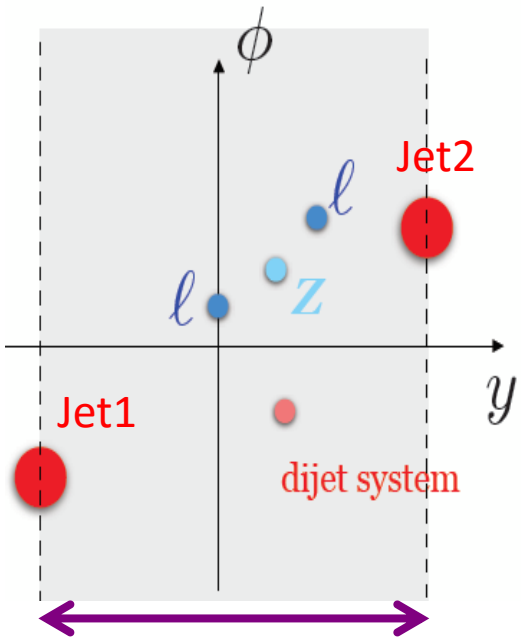
Z+2j production at the LHC











Additional jets of p_T > 25 GeV in the rapidity interval between leading two jets are referred to as gap-jets.

Electroweak Z+2j event selection

Object	Search	Control
Leptons	$\|\eta\| < 2.47,\ p_T > 25$ GeV	
Dilepton pair	$81 < \mathrm{M}_{ll} < 101$ GeV	
	$p_T^{ll} > 20$ GeV	
Jets	$\|y_j\| < 4.4,\ \Delta R_{j,l} \geq 0.3$	
	$p_T^{j1} > 55$ GeV	
	$p_T^{j2} > 45$ GeV	
Dijet system	$m_{jj} > 250$ GeV	
Gap Jets	$n_{jet}^{gap} = 0$	$n_{jet}^{gap} \geq 1$
Z+2j system	$p_T^{balance} < 0.15$	

Basic Z-boson Selection

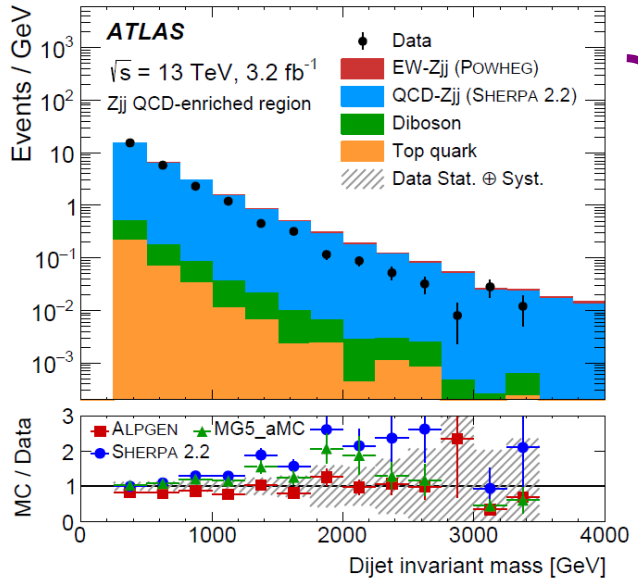
Baseline Di-Jet Selection

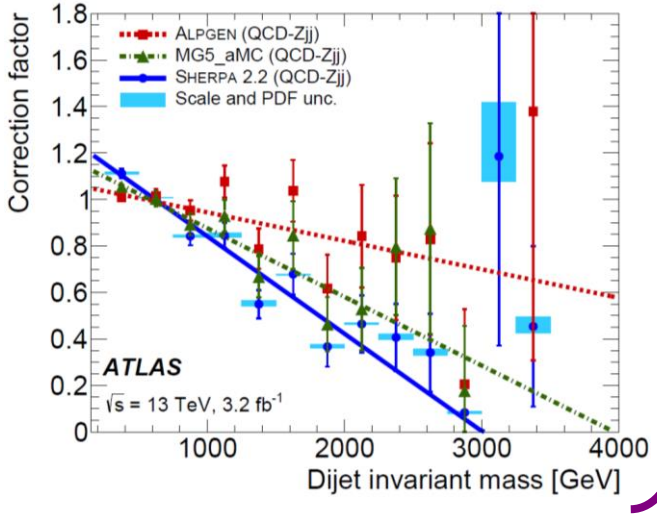
Cuts for Electroweak Extraction

$$p_T^{balance} = \frac{|\sum P_{T,lljets}|}{\sum |P_{T,lljets}|} =$$

p_T of dilepton+jets system over the scalar sum of p_T

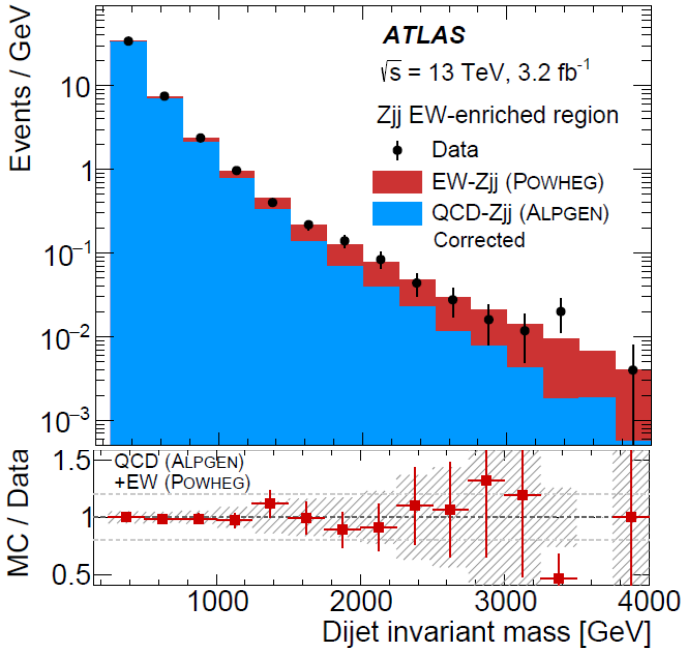
Electroweak Z+2j signal extraction





- Data driven constraint for the strong Z+2j MC derived in control region.
- Strong Z+2j is constrained in the search region.
- Two templates are fitted to data – non Z+2j MC.
  - Template 1: Strong Z+2j (constrained)
  - Template 2: Electroweak Z+2j

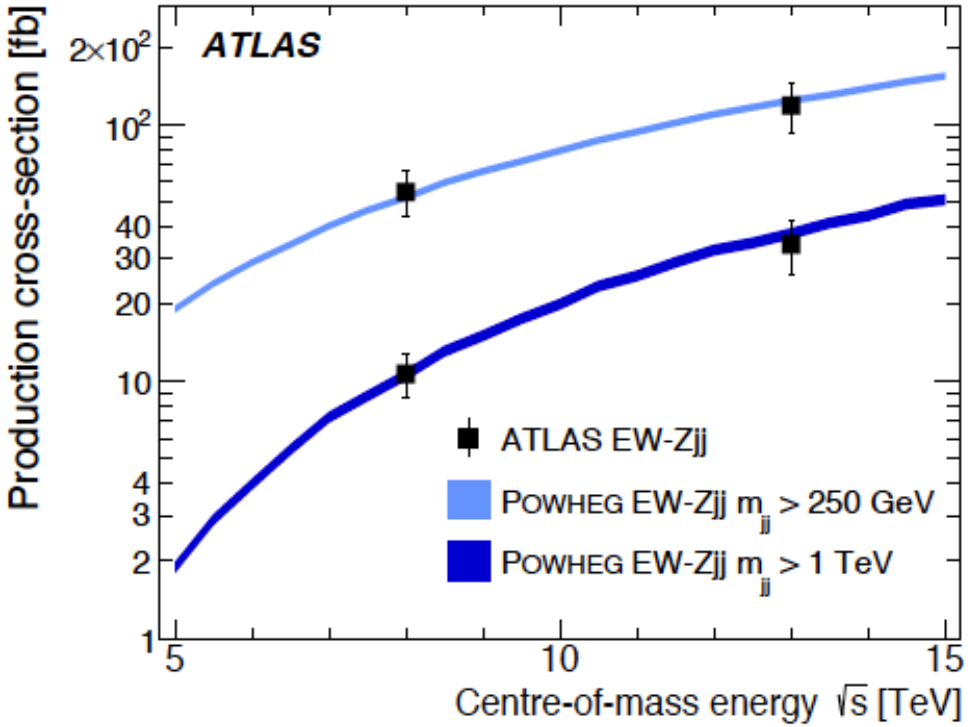
After applying data-driven constraint and two template fit

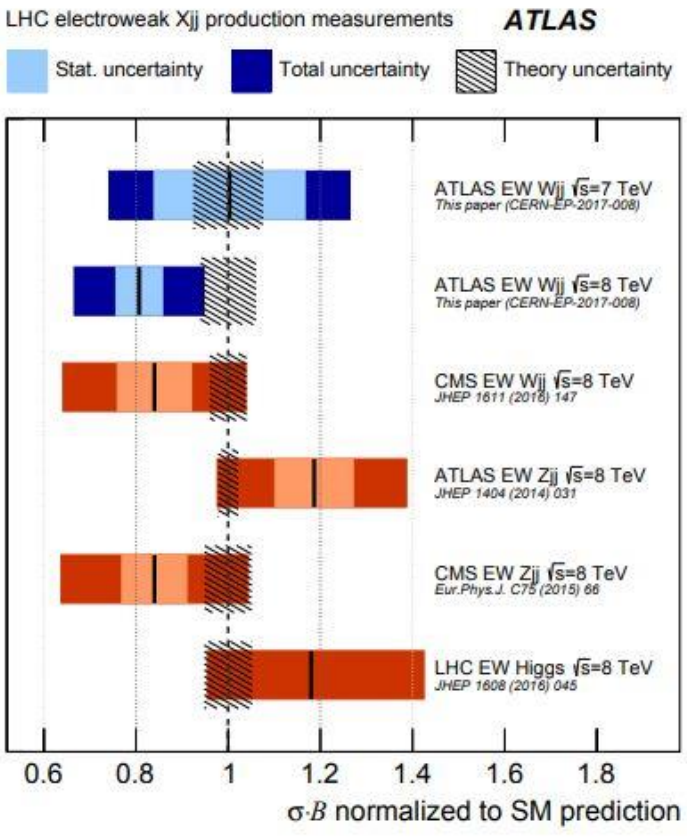


Electroweak Z+2j results summary.

The measured fiducial EW Z+2j cross-section is:

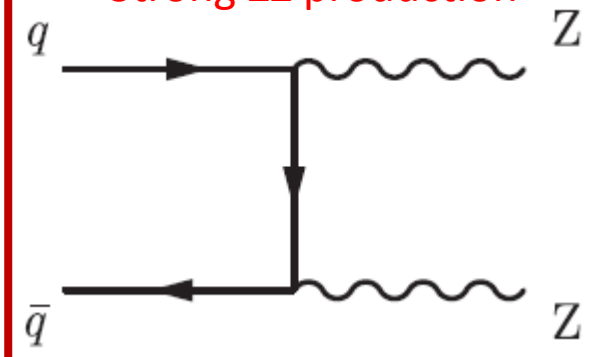
- m_{jj} **> 250 GeV:** σ = 119 ± 16 (stat.) ± 20 (syst.) ± 2 (lumi.) fb
- m_{jj} **> 1000 GeV:** σ = 34.2 ± 5.8 (stat.) ± 5.5 (syst.) ± 0.7 (lumi.) fb



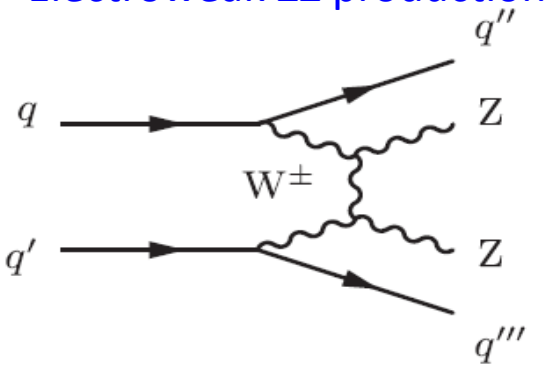


aTGC in ZZ -> llll

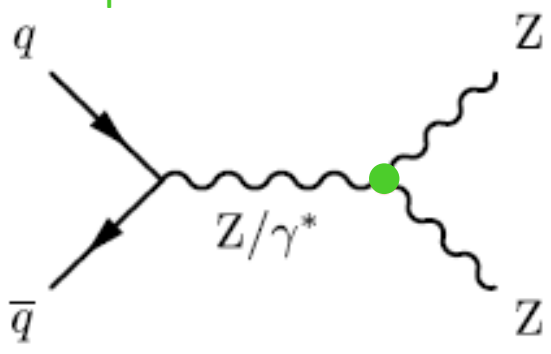
Strong ZZ production



Electroweak ZZ production



ZZ production with aTGC



- Search used leading p_T of Z boson candidate.
- aTGC signal model uses an effective vertex function approach.
- Confidence intervals are set for each aTGC parameter individually and in two dimensions while setting others to zero.

Selection

$$p_T > 5 \text{ GeV} \quad |\eta| < 2.7$$

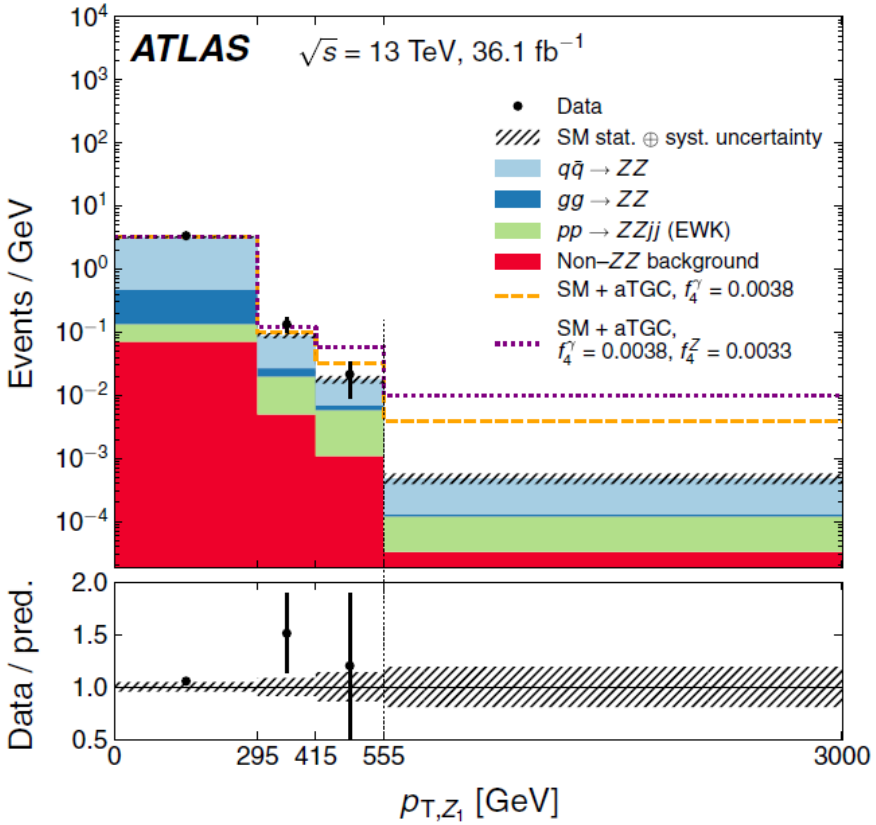
$$p_T^{l1} > 20 \text{ , } p_T^{l2} > 15 \text{ , } p_T^{l3} > 10 \text{ GeV}$$

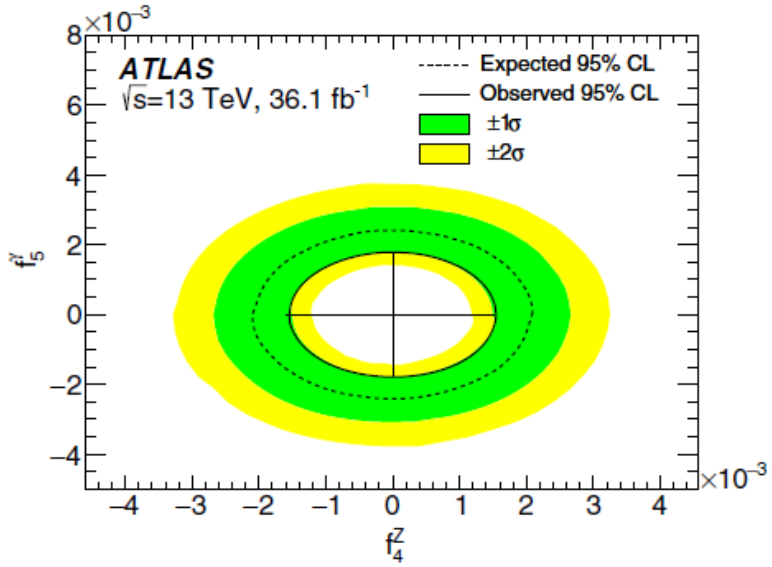
$$|m_{ll}^a - m_Z| + |m_{ll}^b - m_Z|$$

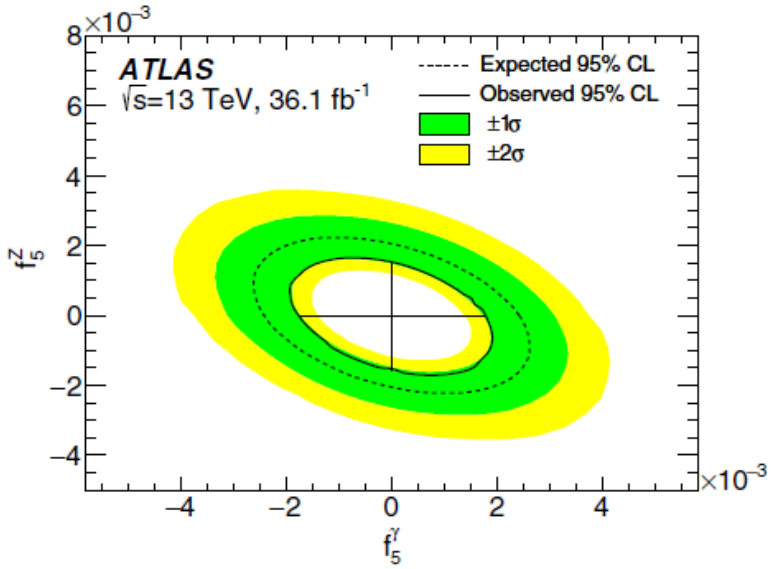
$$66 < M_{ll} < 116 \text{ GeV}$$

aTGC in ZZ -> llll

Coupling strength	Expected 95% CL [$\times 10^{-3}$]	Observed 95% CL [$\times 10^{-3}$]
f_4^γ	−2.4, 2.4	−1.8, 1.8
f_4^Z	−2.1, 2.1	−1.5, 1.5
f_5^γ	−2.4, 2.4	−1.8, 1.8
f_5^Z	−2.0, 2.0	−1.5, 1.5







Conclusion

- The EW production of Z+2j is in good agreement with the Standard Model.
- No significant deviations from the Standard Model are observed for the aTGC coupling strengths.
- By the end of Run-II we will have 150fb^{-1}, this opens the door to high-precision differential measurements that probe the nature of the VBF process

Backup

Data driven constraint on strong Zjj

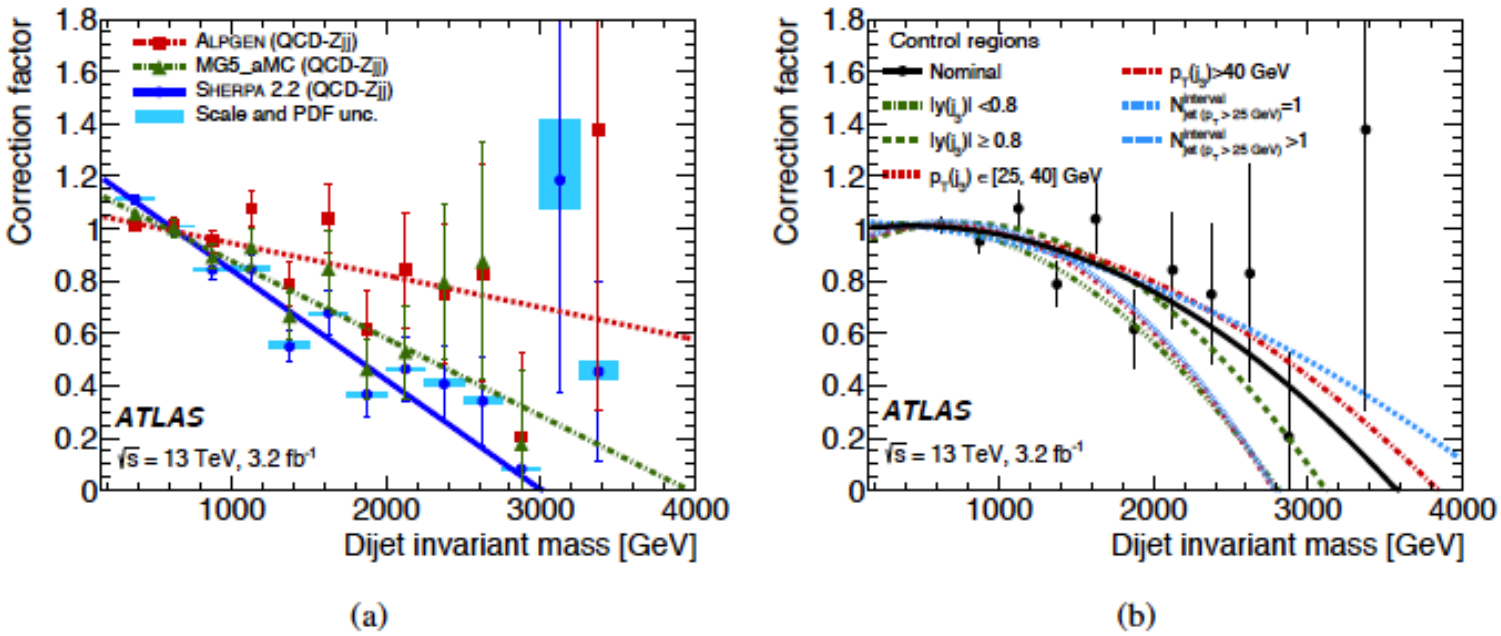


Figure 3: Binned data-to-simulation normalised ratio shape correction factors as a function of dijet invariant mass in the QCD-enriched region. (a) Ratio for three different QCD-*Zjj* MC samples with uncertainties corresponding to the combined statistical uncertainties in the data and QCD-Zjj MC samples added in quadrature. Scale and PDF uncertainties in SHERPA predictions are indicated by the shaded bands. Lines represent fits to the ratios using a linear fit. (b) Ratio for subregions of the QCD-enriched region for the ALPGEN MC sample. Curves represent the result of fits with a quadratic function for the various subregions.

Yields for fiducial regions

	Composition [%]					
Process	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
QCD-Zjj	94.2 ± 0.4	86.8 ± 1.6	92.3 ± 0.4	93.4 ± 0.9	72.9 ± 2.1	95.4 ± 0.8
EW-Zjj	1.5 ± <0.1	10.6 ± 0.2	2.6 ± <0.1	4.8 ± <0.1	26.1 ± 0.5	1.6 ± <0.1
Diboson	1.6 ± <0.1	1.5 ± 0.7	2.0 ± 0.5	1.0 ±0.5	0.8 ± 0.4	1.8 ±0.4
$t\bar{t}$	2.6 ± <0.1	1.1 ± 0.1	3.1 ± 0.1	0.7 ± <0.1	0.1 ± 0.1	1.2 ± 0.1
Single-t	<0.2	<0.2	<0.2	<0.1	<0.1	<0.1
Multijet	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Total expected	64800 ± 130 ± 5220	2220 ± 20 ± 200	21900 ± 40 ± 1210	11100 ± 50 ± 520	640 ± 10 ± 40	7120 ± 30 ± 880
Total observed	67472	1471	22461	11630	490	6453

Table 2: Estimated composition (in percent) of the data samples selected in the six Zjj fiducial regions for the dielectron and dimuon channels combined, using the EW-Zjj sample from POWHEG, and the QCD-Zjj sample from SHERPA (normalised using NNLO predictions for the inclusive Z cross-section calculated with FEWZ). Uncertainties in the sample contributions are statistical only. Also shown are the total expected yields and the total observed yields in each fiducial region. Uncertainties in the total expected yields are statistical (first) and systematic (second), see Section 5.4 for details.

Inclusive Zjj cross sections

Fiducial region	Inclusive Zjj cross-sections [pb]			
	Measured value ± stat. ± syst. ± lumi.	Prediction		
		SHERPA (QCD-Zjj) +POWHEG (EW-Zjj)	MG5_aMC (QCD-Zjj) +POWHEG (EW-Zjj)	ALPGEN (QCD-Zjj) +POWHEG (EW-Zjj)
Baseline	13.9 ± 0.1 ± 1.1 ± 0.3	13.5 ± 1.9	15.2 ± 2.2	11.7 ± 1.7
High-p_{T}	4.77 ± 0.05 ± 0.27 ± 0.10	4.7 ± 0.8	5.5 ± 0.9	4.2 ± 0.7
EW-enriched	2.77 ± 0.04 ± 0.13 ± 0.06	2.7 ± 0.2	3.6 ± 0.3	2.4 ± 0.2
QCD-enriched	1.34 ± 0.02 ± 0.17 ± 0.03	1.5 ± 0.4	1.4 ± 0.3	1.1 ± 0.3
High-mass	0.30 ± 0.01 ± 0.03 ± 0.01	0.46 ± 0.11	0.40 ± 0.09	0.27 ± 0.06
EW-enriched ($m_{jj} > 1$ TeV)	0.118 ± 0.008 ± 0.006 ± 0.002	0.156 ± 0.019	0.185 ± 0.023	0.120 ± 0.015

Table 3: Measured and predicted inclusive Zjj production cross-sections in the six fiducial regions defined in Table 1. For the measured cross-sections, the first uncertainty given is statistical, the second is systematic and the third is due to the luminosity determination. For the predictions, the statistical uncertainty is added in quadrature to the systematic uncertainties arising from the PDFs and factorisation and renormalisation scale variations.

Zjj systematics

Source	Relative systematic uncertainty [%] $\sigma_{\text{EW}}^{m_{jj}>250\text{ GeV}}$	$\sigma_{\text{EW}}^{m_{jj}>1\text{ TeV}}$
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

Table 4: Systematic uncertainties contributing to the measurement of the EW-Zjj cross-sections for $m_{jj} > 250$ GeV and $m_{jj} > 1$ TeV. Uncertainties are grouped into EW-Zjj signal modelling, QCD-Zjj background modelling, QCD-EW interference, non-Zjj backgrounds, and experimental sources.

ZZ yields per channel

TABLE II. Observed and predicted yields, using the nominal SHERPA setup for the signal predictions. All statistical and systematic uncertainties are included in the prediction uncertainties. An alternative total prediction is given, using SHERPA reweighted to the total NNLO prediction from MATRIX with NLO EW corrections, adding the contribution of the EW-$ZZjj$ process generated with SHERPA, to predict the signal yield. A second alternative total prediction, identical to the nominal SHERPA setup, except using POWHEG + PYTHIA with NNLO QCD and NLO EW corrections applied event by event to simulate the $q\bar{q}$-initiated process, is shown at the bottom.

Contribution	$4e$	$2e2\mu$	4μ	Combined
Data	249	465	303	1017
Total prediction (SHERPA)	198^{+16}_{-14}	469^{+35}_{-31}	290^{+22}_{-21}	958^{+70}_{-63}
Signal ($q\bar{q}$-initiated)	168^{+14}_{-13}	400^{+31}_{-28}	246^{+19}_{-18}	814^{+63}_{-57}
Signal (gg-initiated)	21.3 ± 3.5	50.2 ± 8.2	29.7 ± 4.9	101 ± 17
Signal (EW-$ZZjj$)	4.36 ± 0.42	10.23 ± 0.72	6.43 ± 0.55	21.0 ± 1.2
$ZZ \to \tau^+\tau^-[\ell^+\ell^-, \tau^+\tau^-]$	0.59 ± 0.09	0.55 ± 0.08	0.55 ± 0.09	1.69 ± 0.16
Triboson	0.68 ± 0.21	1.50 ± 0.46	0.96 ± 0.30	3.14 ± 0.30
$t\bar{t}Z$	0.81 ± 0.25	1.86 ± 0.56	1.42 ± 0.43	4.1 ± 1.2
Misid. lepton background	2.1 ± 2.1	4.9 ± 3.9	5.3 ± 5.2	12.3 ± 8.3
Total prediction (MATRIX + corrections)	197^{+15}_{-14}	470^{+34}_{-31}	286^{+22}_{-21}	953^{+69}_{-64}
Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA)	193 ± 11	456 ± 24	286 ± 17	934 ± 50

ZZ systematics

TABLE III. Relative uncertainties in percent of the predicted integrated signal yields after event selection, derived using the nominal SHERPA setup. All uncertainties are rounded to one decimal place.

Source	Effect on total predicted yield [%]
MC statistical uncertainty	0.4
Electron efficiency	0.9
Electron energy scale & resolution	<0.1
Muon efficiency	1.7
Muon momentum scale & resolution	<0.1
Pileup modeling	1.2
Luminosity	3.2
QCD scales	$^{+5.2}_{-4.7}$
PDFs	$^{+2.7}_{-1.7}$
Background prediction	0.9
Total	$^{+7.4}_{-6.6}$

TABLE IV. Relative uncertainties of the correction factor C_{ZZ} by channel, given in percent. All uncertainties are rounded to one decimal place. Uncertainties that do not apply in a given channel are marked with a dash (–). They are either exactly zero or very close to zero.

Source	$4e$	$2e2\mu$	4μ
MC statistical uncertainty	0.4	0.2	0.1
Electron efficiency	2.0	1.0	–
Electron energy scale & resolution	0.1	<0.1	–
Muon efficiency	–	1.6	3.2
Muon momentum scale & resolution	–	<0.1	0.1
Pileup modeling	1.3	0.8	2.0
QCD scales & PDFs	$^{+0.4}_{-0.8}$	$^{+0.3}_{-0.4}$	$^{+0.3}_{-0.6}$
Event generator	1.8	1.8	0.2
Total	3.1	2.8	3.8