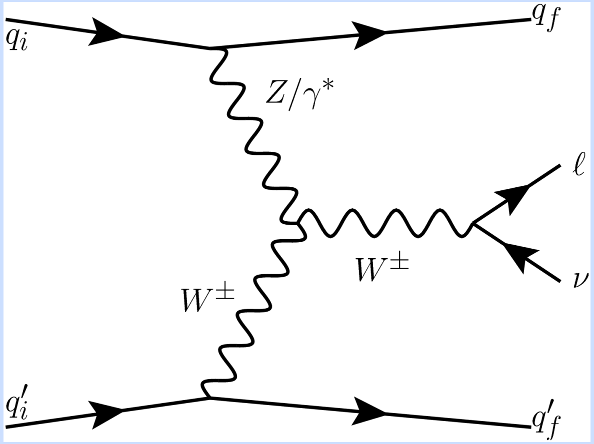
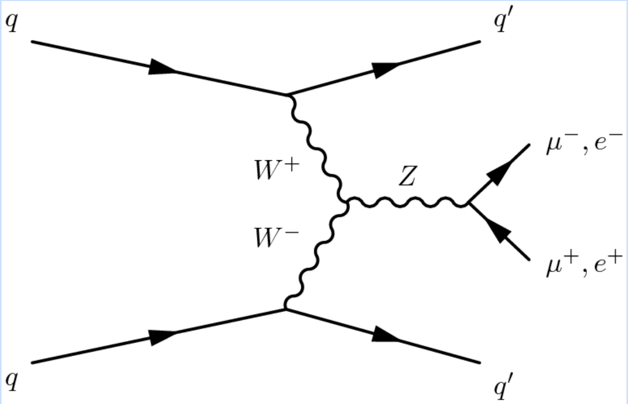
Measurements of vector boson fusion with the ATLAS detector



Chris Hays,
Oxford University



on behalf of the ATLAS Collaboration

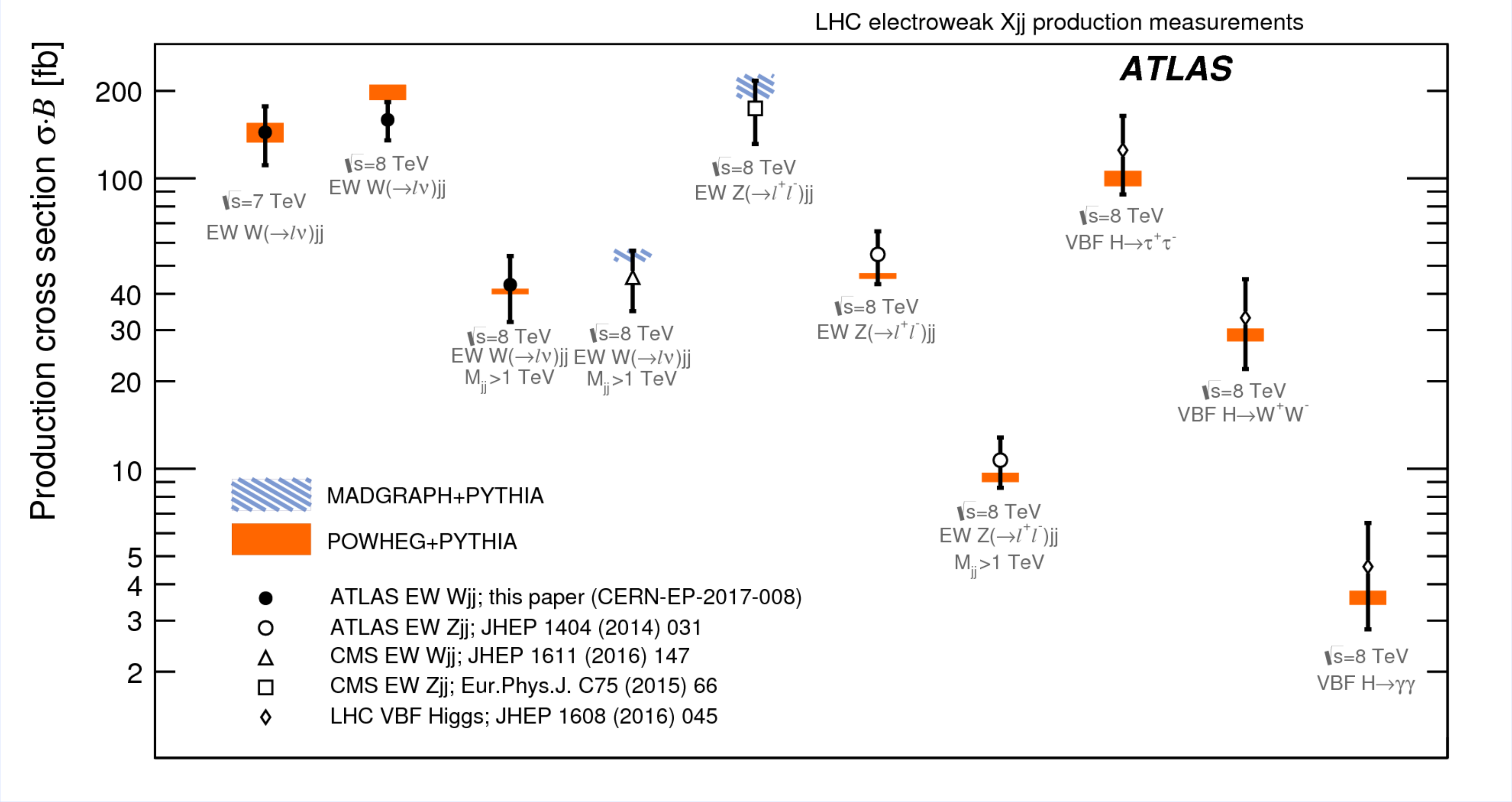
25th International Workshop on Deep Inelastic Scattering
6 April 2017

Motivation

Large cross sections and clean signatures of W→lν and Z→ll production allow the most precise probes of electroweak boson production in a vector-boson fusion topology

Sensitive to triple-gauge couplings

Validate uncertainties common to VBF Higgs measurements

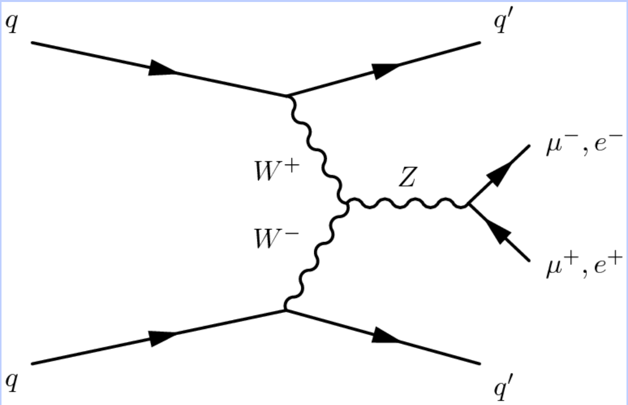


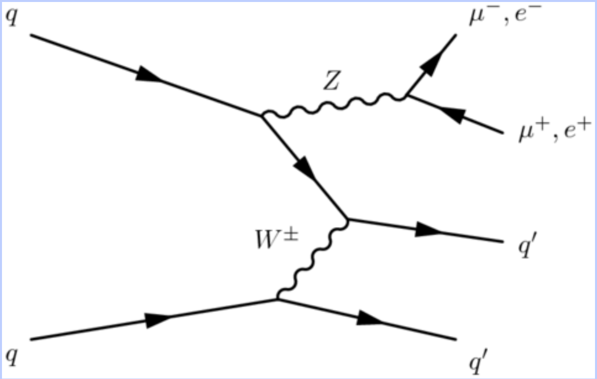
ATLAS VBF W & Z measurements

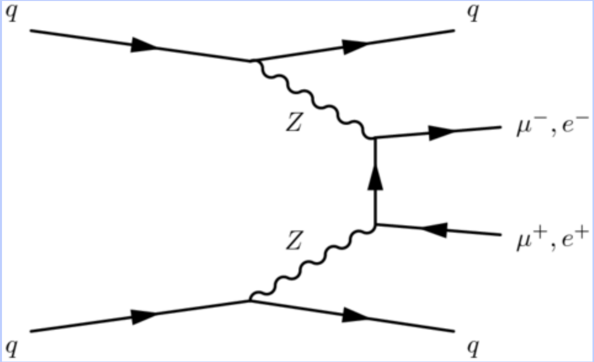
Cross sections in several fiducial regions

Differential cross sections of QCD and EW Vjj production in VBF fiducial regions

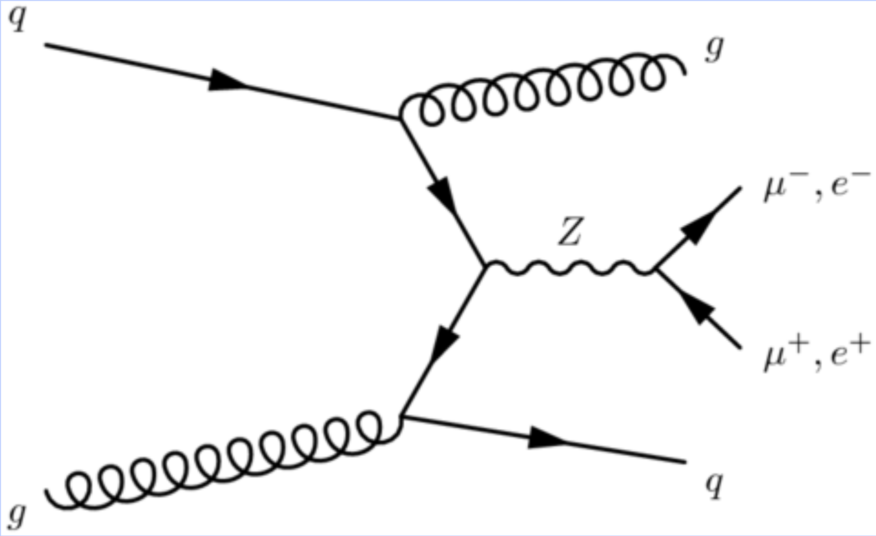
Constraints on anomalous triple-gauge couplings







EW Zjj production at high m_{jj}
4 EW vertices



QCD Zjj production
2 EW vertices

VBF Z production @ 8 TeV

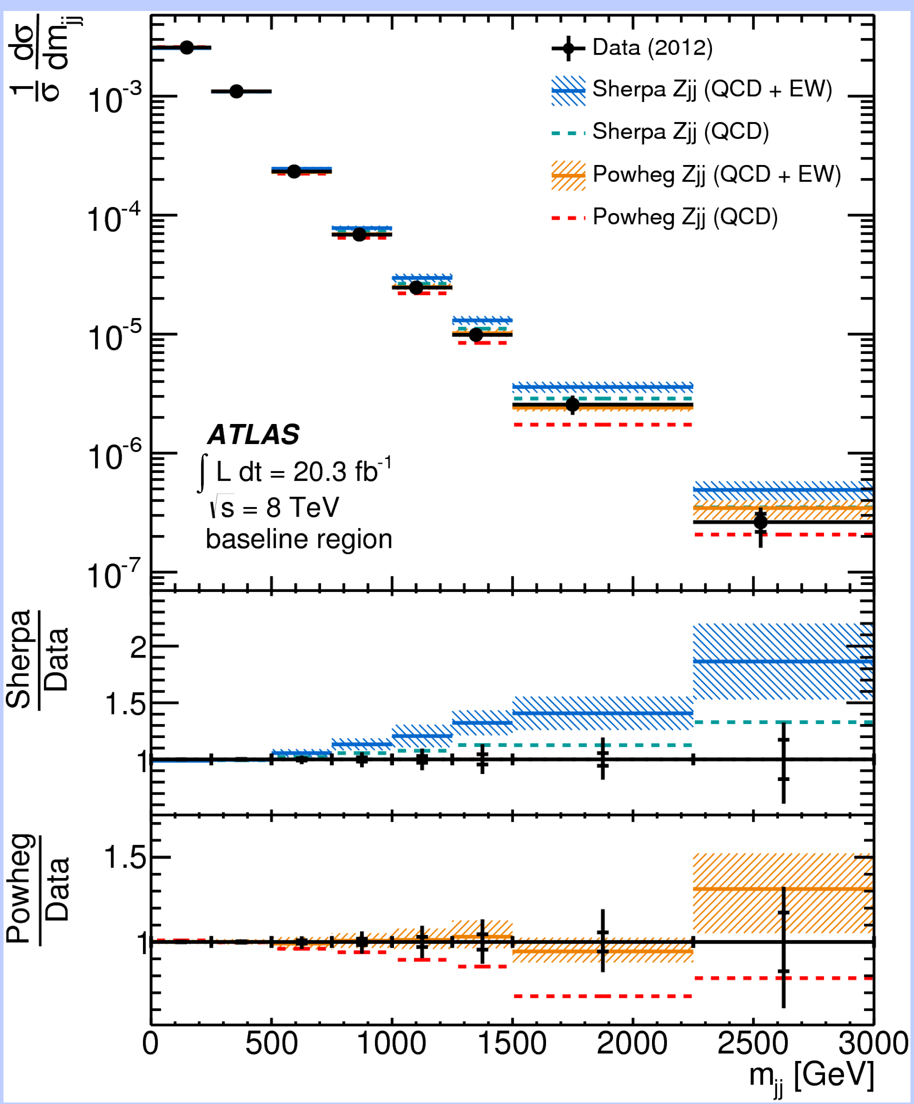
JHEP 04 (2014) 031

t-channel production gives a signature of small-angle scattering: good S/B at high m_{jj}

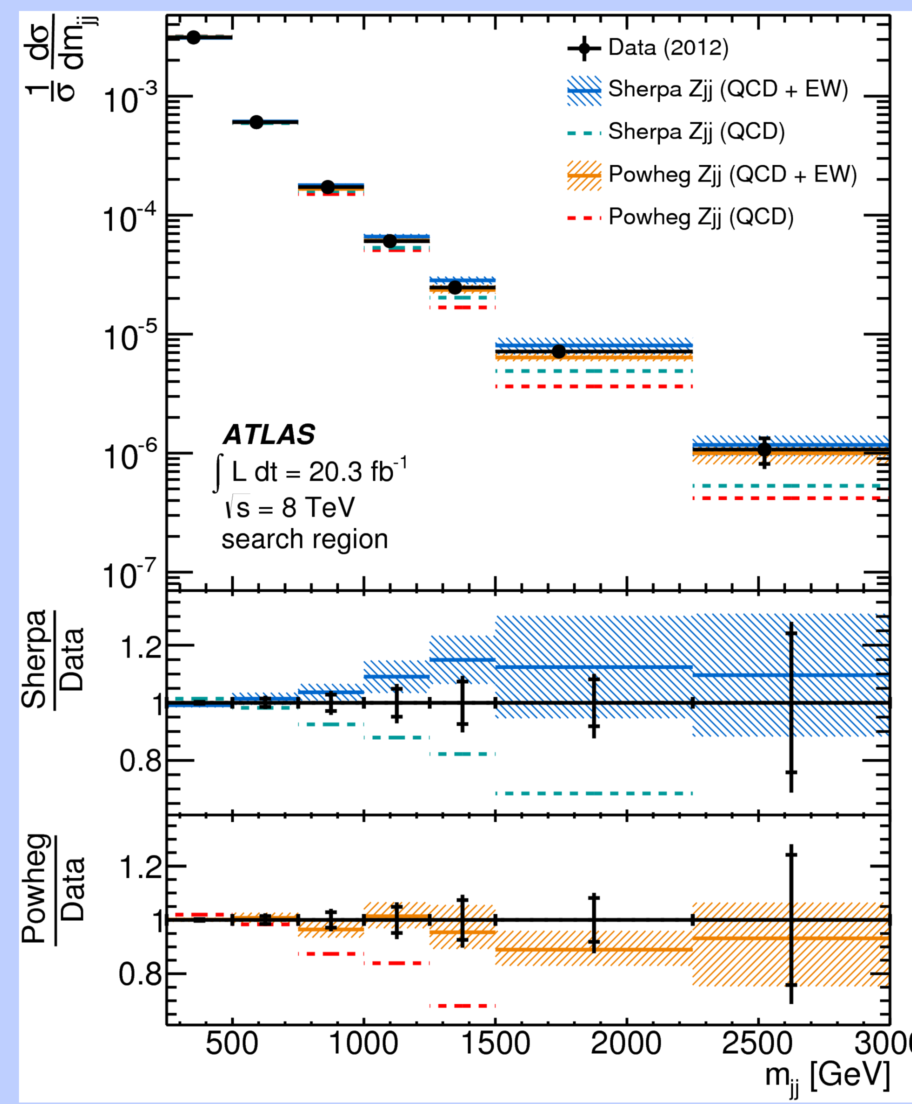
Jet p_T > 50, 40 GeV

Two m_{jj} regions defined: m_{jj} > 250 GeV and m_{jj} > 1 TeV

Further enhance signal by requiring no additional jets in rapidity spanned by two jets



No jet in gap



Sherpa: LO

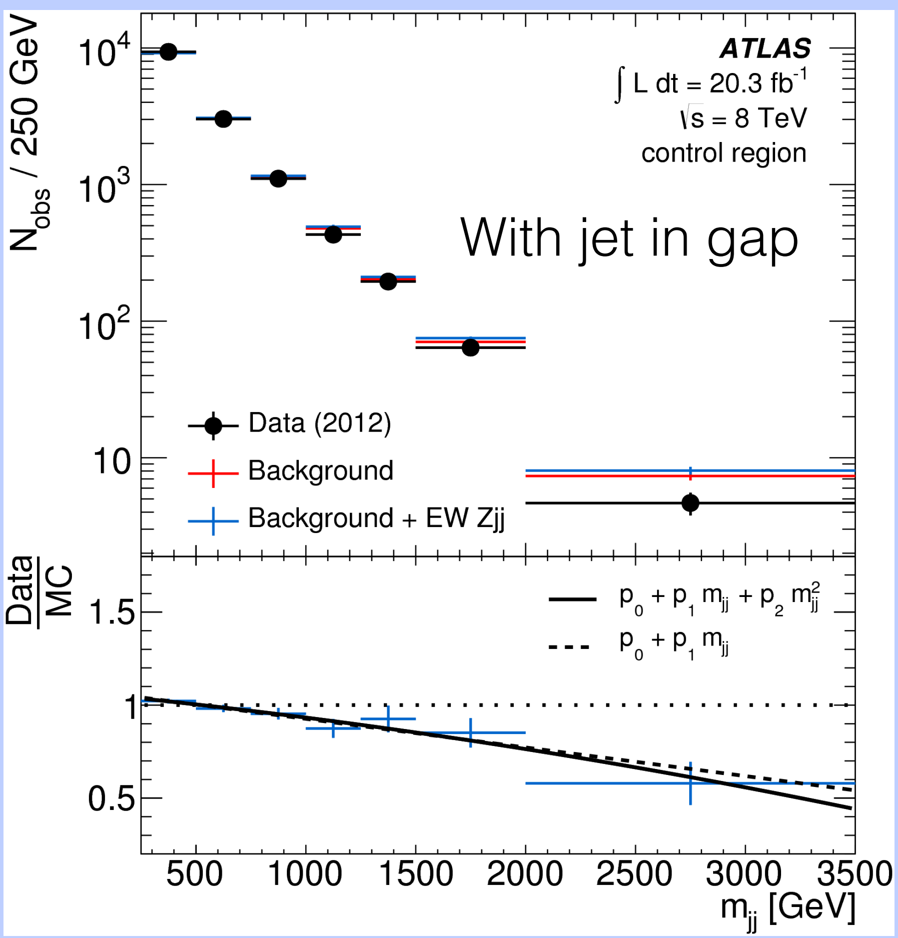
Powheg: NLO

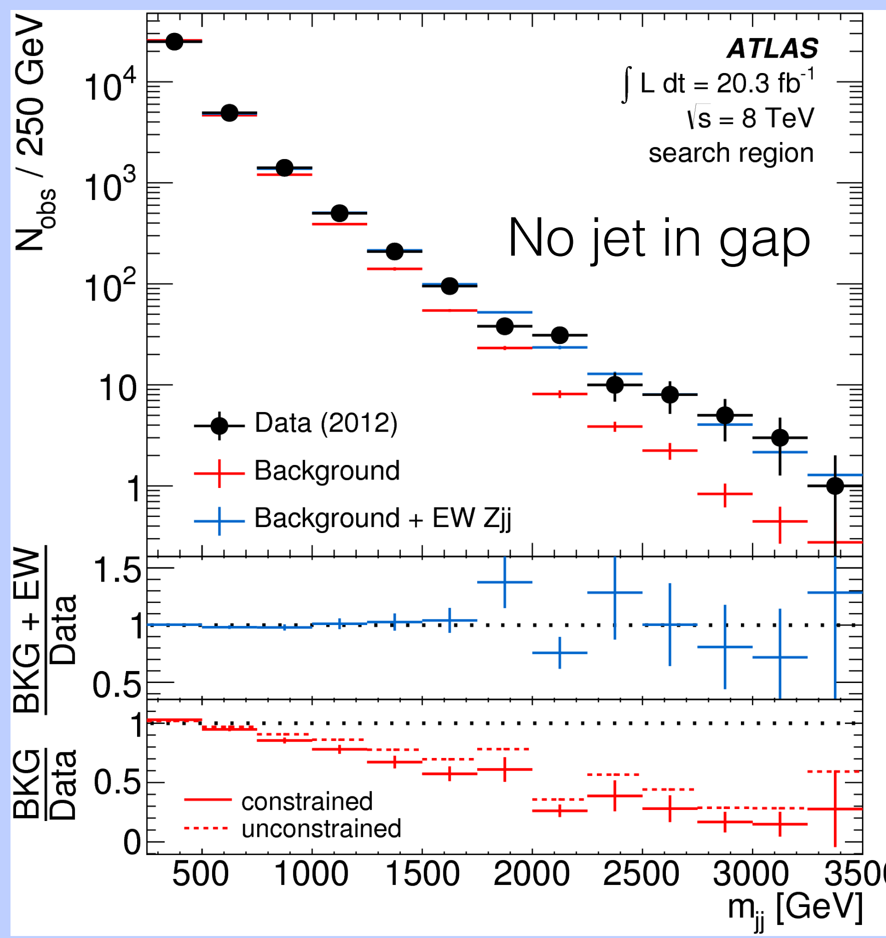
VBF Z production @ 8 TeV

JHEP 04 (2014) 031

Sherpa does not model m_{jj} shape well for QCD Zjj production
Apply a correction to this shape based on events with an additional jet in the gap

Measure EW Zjj production after correction
Also constrain anomalous couplings using events with m_{jj} > 1 TeV





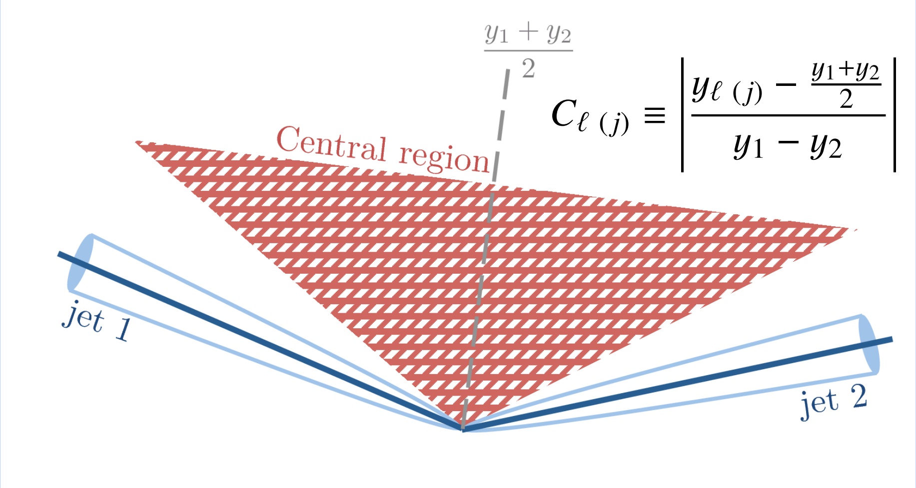
Region	Measurement	Powheg
m_{jj} > 250 GeV	**σ_{EW} = 54.7** ±4.6 (stat) $^{+9.8}_{-10.4}$ (sys) ±1.5 (lum) fb	**σ_{EW} = 46.1** ±0.2 (stat) $^{+0.3}_{-0.2}$ (scale) ±0.8 (PDF) ±0.5 (model)
m_{jj} > 1 TeV	**σ_{EW} = 10.7** ±0.9 (stat) ±1.9 (sys) ±0.3 (lum) fb	**σ_{EW} = 9.4** ±0.1 (stat) ±0.2 (scale) ±0.2 (PDF) ±0.1 (model)

VBF W production @ 7 & 8 TeV

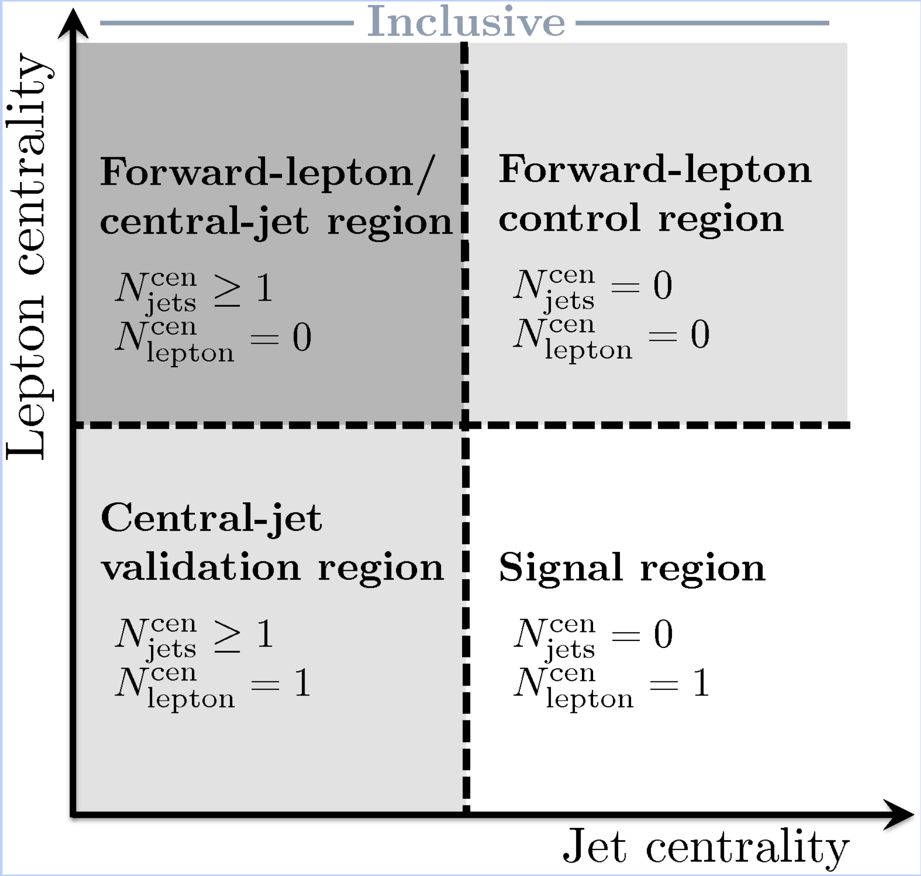
arXiv:1703.04362

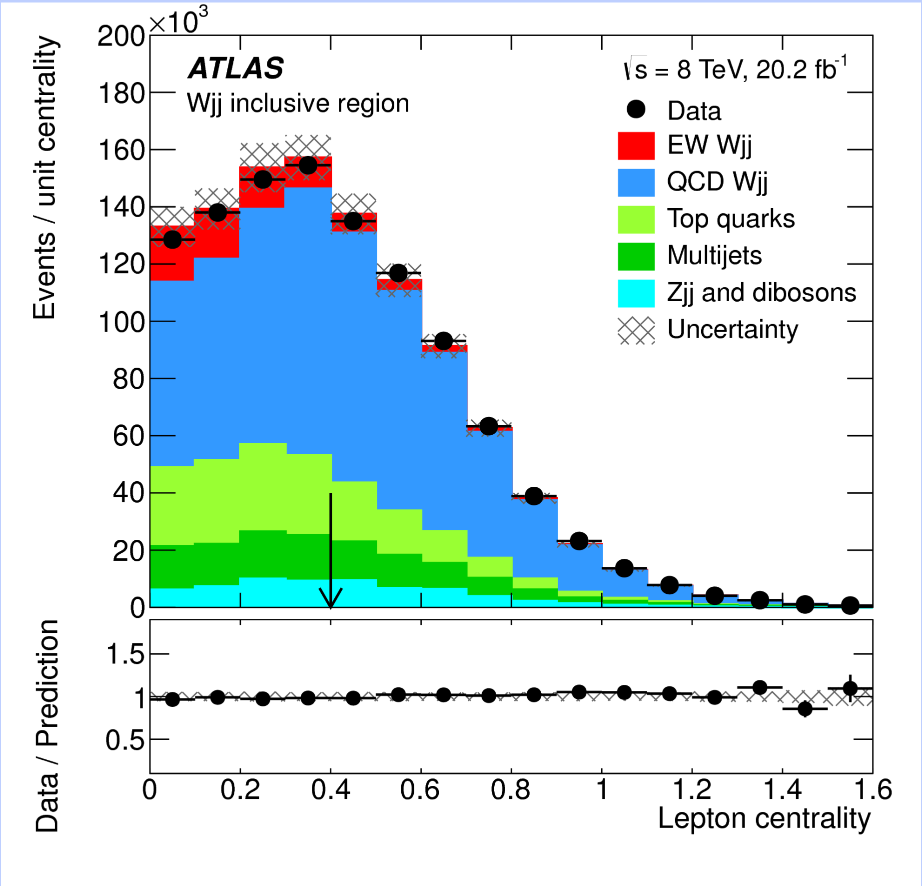
Higher cross section allows:

Most precise measurement of VBF boson production
Only measurement of VBF boson production at 7 TeV
Differential measurements of VBF boson production



Similar selection to VBF Z measurement
Powheg MiNLO used to model m_{jj} distribution

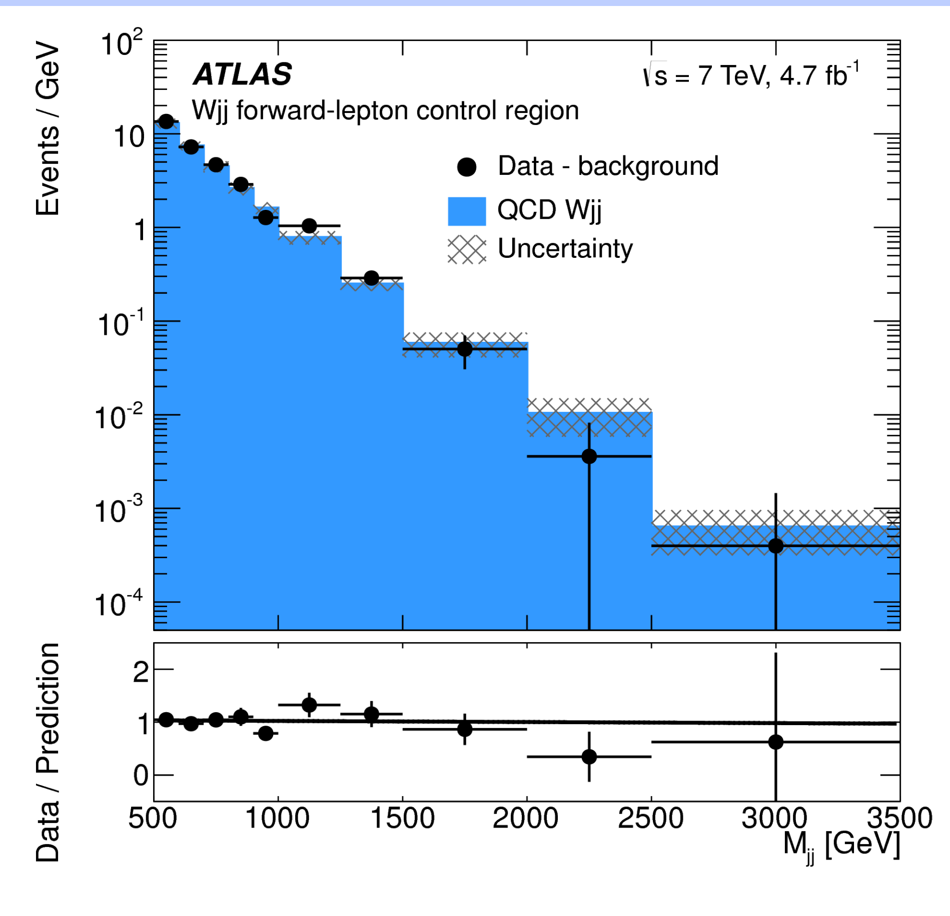


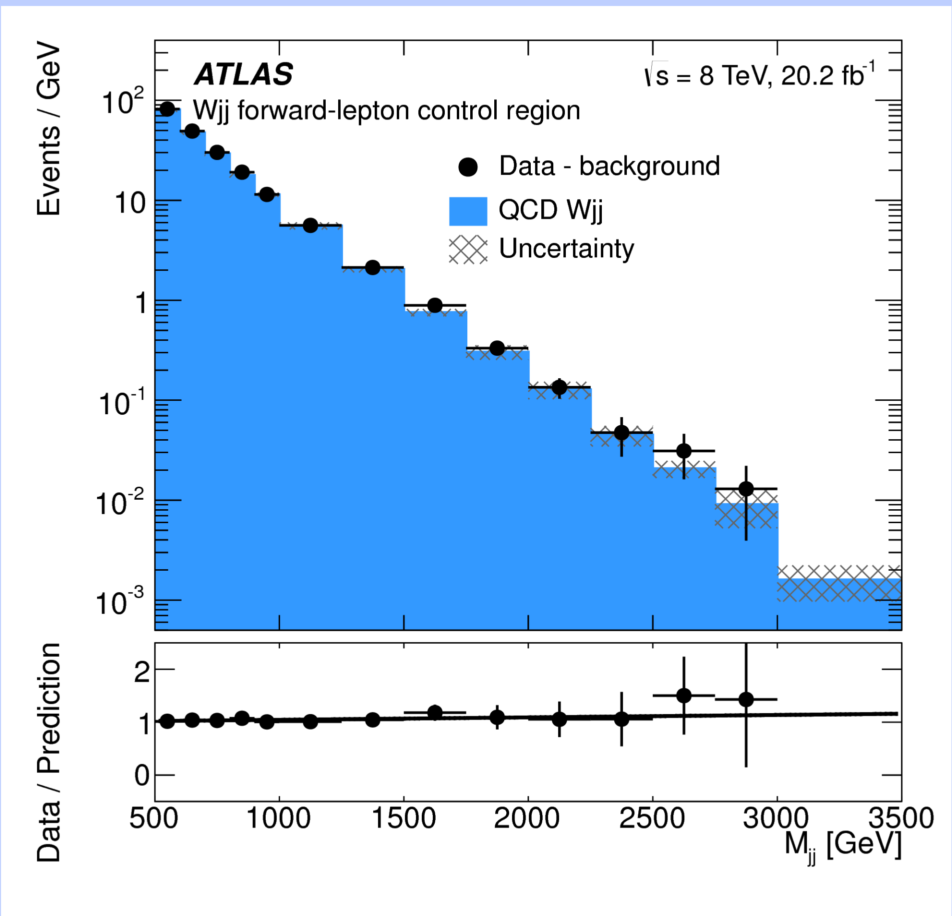


VBF W production @ 7 & 8 TeV

arXiv:1703.04362

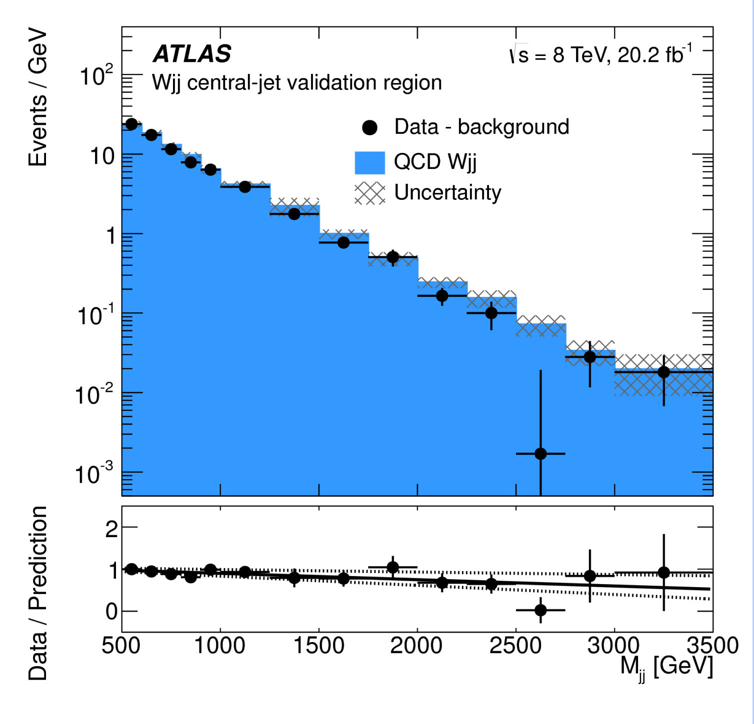
Apply a correction to the m_{jj} shape to reduce uncertainties (using “forward-lepton region”)
Test correction in region where there is an additional jet in the gap





No jet in gap
(to derive correction)

With jet in gap
(to validate correction)

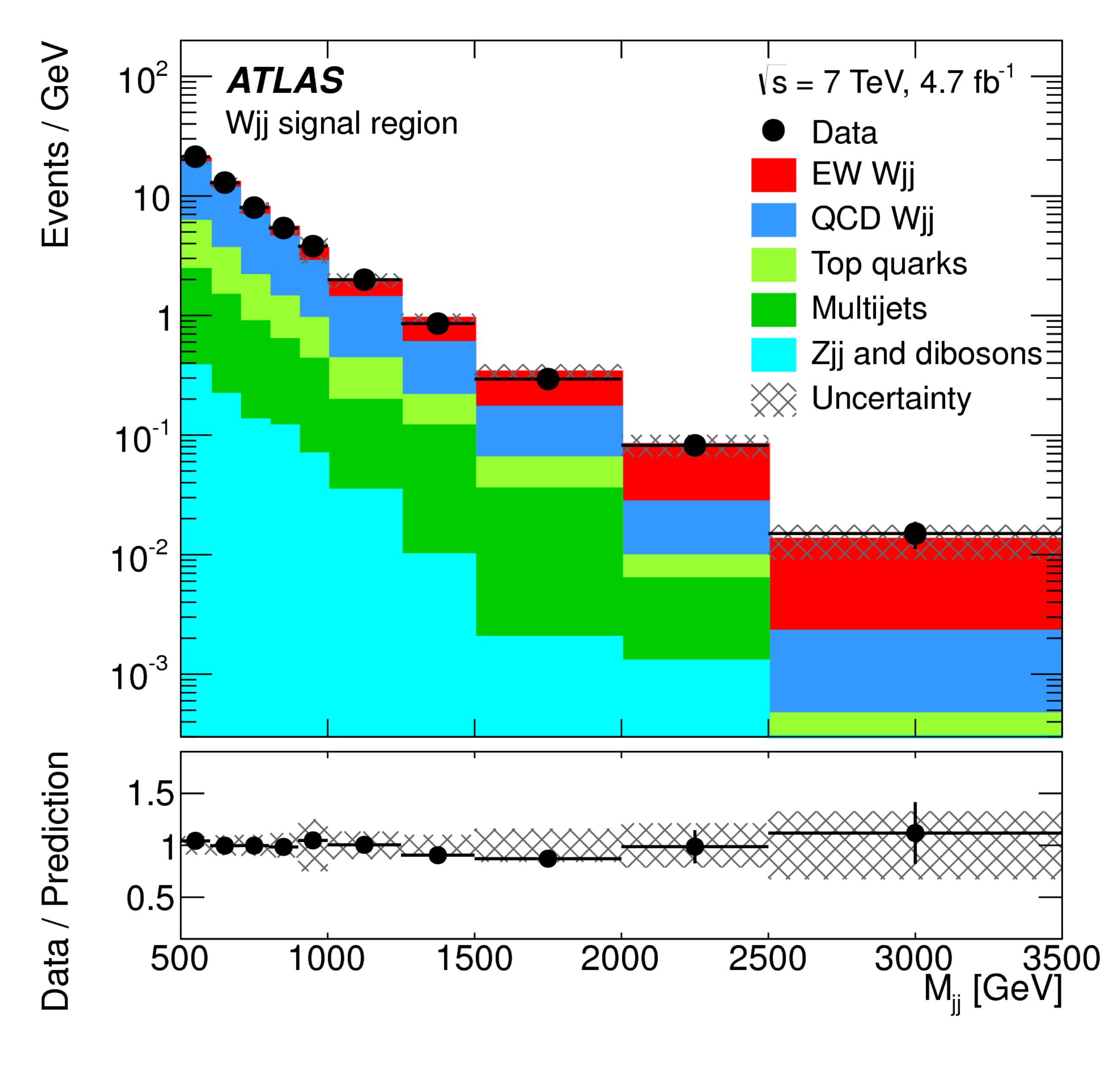


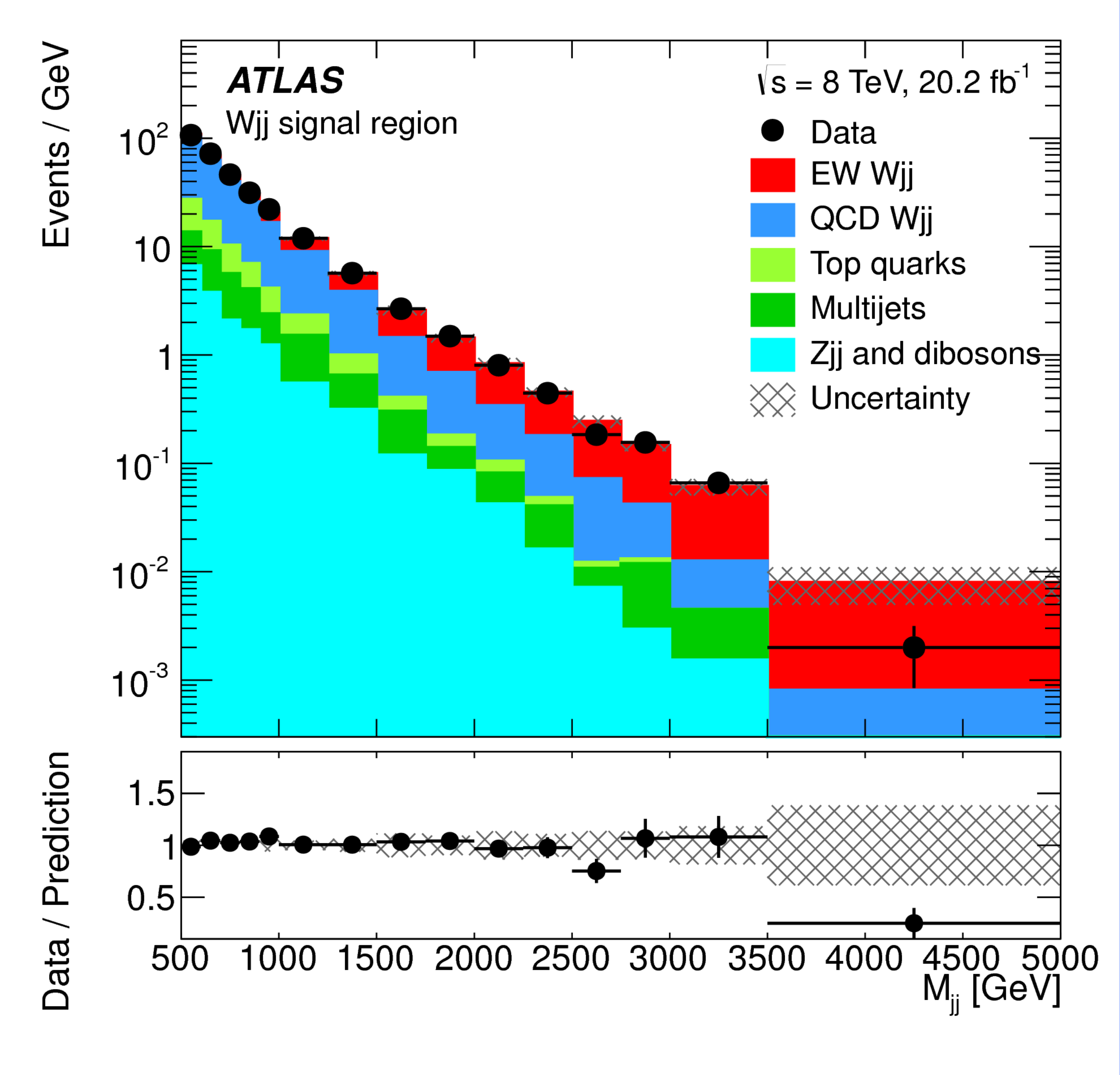
Correction reduces total uncertainty on measurement of σ/σ_{SM} from 0.18 to 0.14

VBF W production @ 7 & 8 TeV

arXiv:1703.04362

Fit m_{jj} for the normalizations of QCD Wjj and EW Wjj





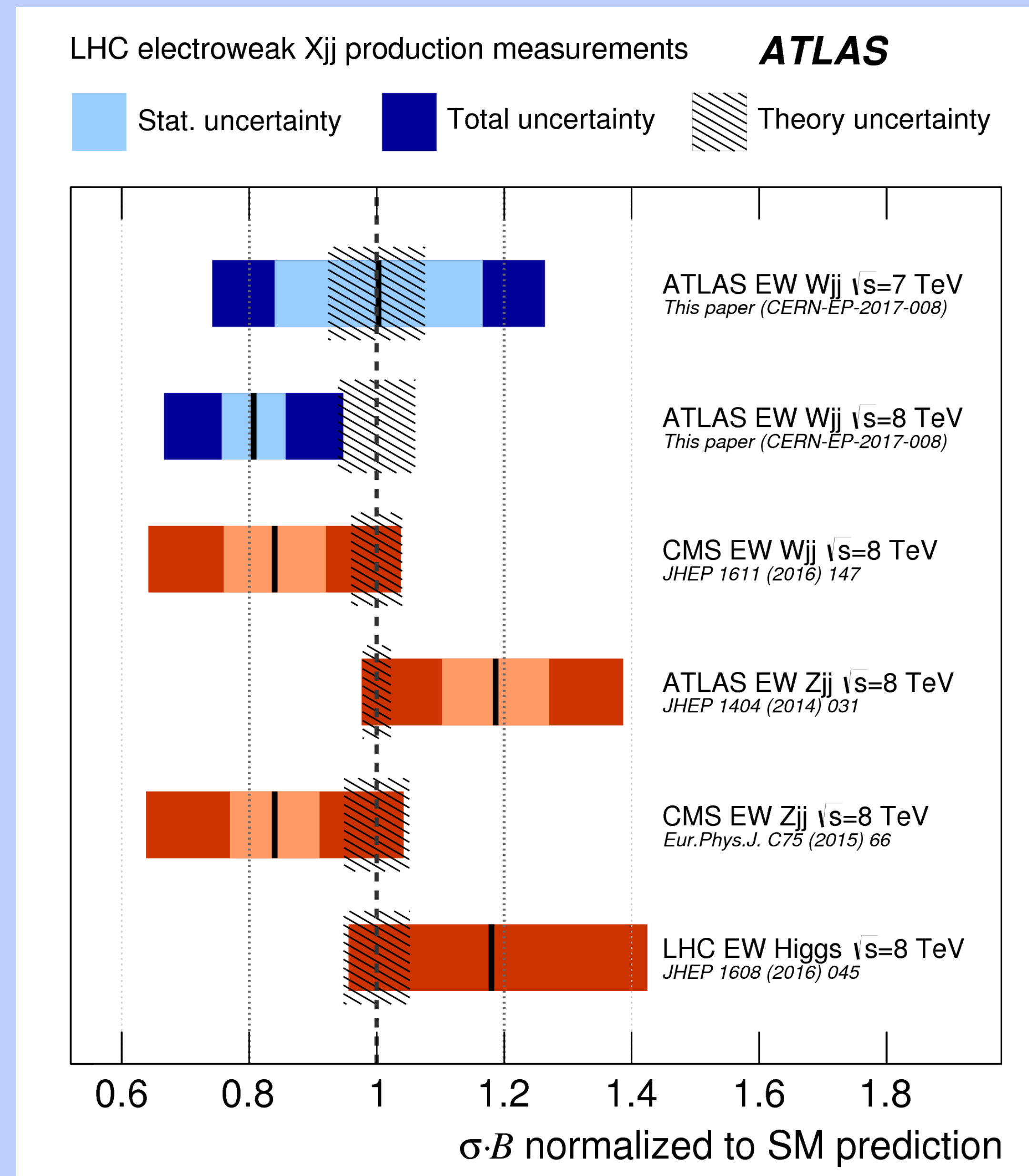
VBF W production @ 7 & 8 TeV

arXiv:1703.04362

$\sqrt{s}$	$\sigma^{\text{fid}}_{\text{meas}}$ [fb]	$\sigma^{\text{fid}}_{\text{SM}}$ [fb]	Acceptance $\mathcal{A}$	$\sigma^{\text{inc}}_{\text{meas}}$ [fb]
7 TeV	144 ± 23 (stat) ± 23 (exp) ± 13 (th)	144 ± 11	0.053 ± 0.004	2760 ± 670
8 TeV	159 ± 10 (stat) ± 17 (exp) ± 20 (th)	198 ± 12	0.058 ± 0.003	2890 ± 510

Source	Uncertainty in μ_{EW} 7 TeV	8 TeV
Statistical		
Signal region	0.094	0.028
Control region	0.127	0.044
Experimental		
Jet energy scale (η intercalibration)	0.124	0.053
Jet energy scale and resolution (other)	0.096	0.059
Luminosity	0.018	0.019
Lepton and $E_{\text{T}}^{\text{miss}}$ reconstruction	0.021	0.012
Multijet background	0.064	0.019
Theoretical		
MC statistics (signal region)	0.027	0.026
MC statistics (control region)	0.029	0.019
EW Wjj (scale and parton shower)	0.012	0.031
QCD Wjj (scale and parton shower)	0.043	0.018
Interference (EW and QCD Wjj)	0.037	0.032
Parton distribution functions	0.053	0.052
Other background cross sections	0.002	0.002
EW Wjj cross section	0.076	0.061
Total	0.26	0.14

CT10 vs NNPDF



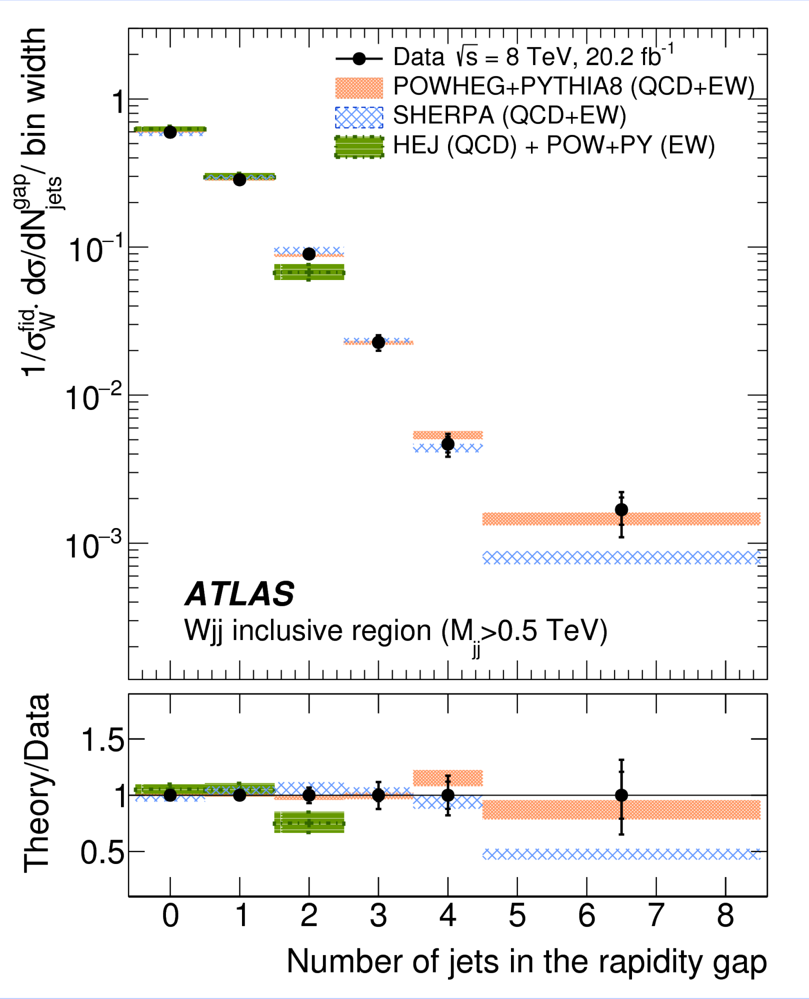
VBF W production @ 8 TeV

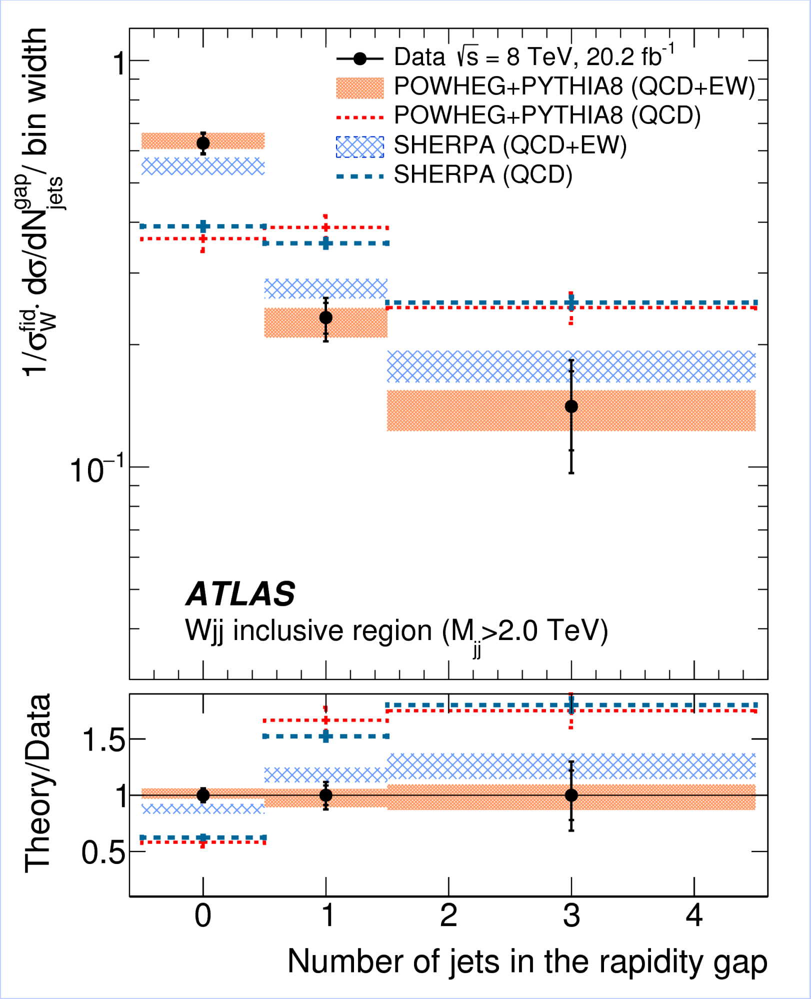
arXiv:1703.04362

Perform differential measurements of QCD+EW and EW Wjj production
Probe the various jet and lepton centrality phase spaces + four m_{jj} thresholds

# of jets in gap between leading jets is an important distribution for extracting EW Wjj

Can also be quantified as the fraction of events with no jet in the gap (the "Jet-veto efficiency")



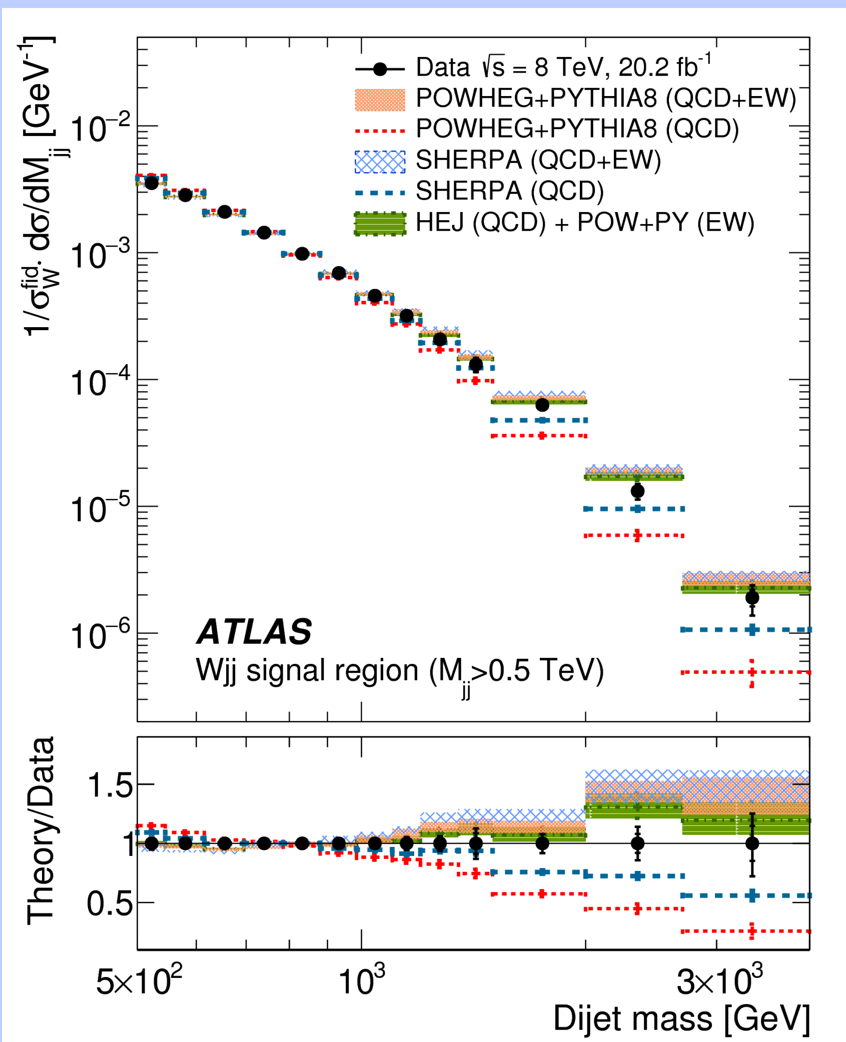


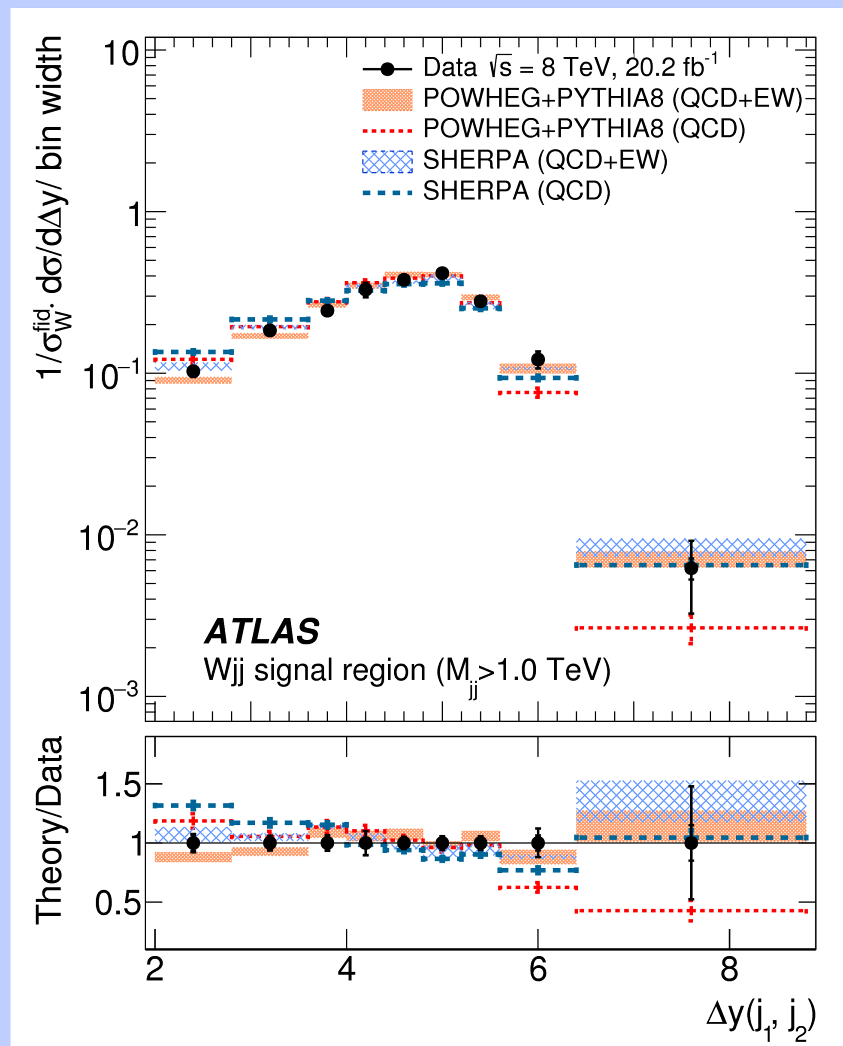
	Jet-veto efficiency			
	$M_{jj} > 0.5$ TeV	$M_{jj} > 1.0$ TeV	$M_{jj} > 1.5$ TeV	$M_{jj} > 2.0$ TeV
Data	0.596 ± 0.014	0.54 ± 0.02	0.55 ± 0.03	0.63 ± 0.04
Powheg +Pythia8 (QCD+EW)	0.597 ± 0.005	0.55 ± 0.01	0.57 ± 0.02	0.63 ± 0.03
Powheg +Pythia8 (QCD)	0.569 ± 0.002	0.45 ± 0.01	0.39 ± 0.01	0.36 ± 0.03

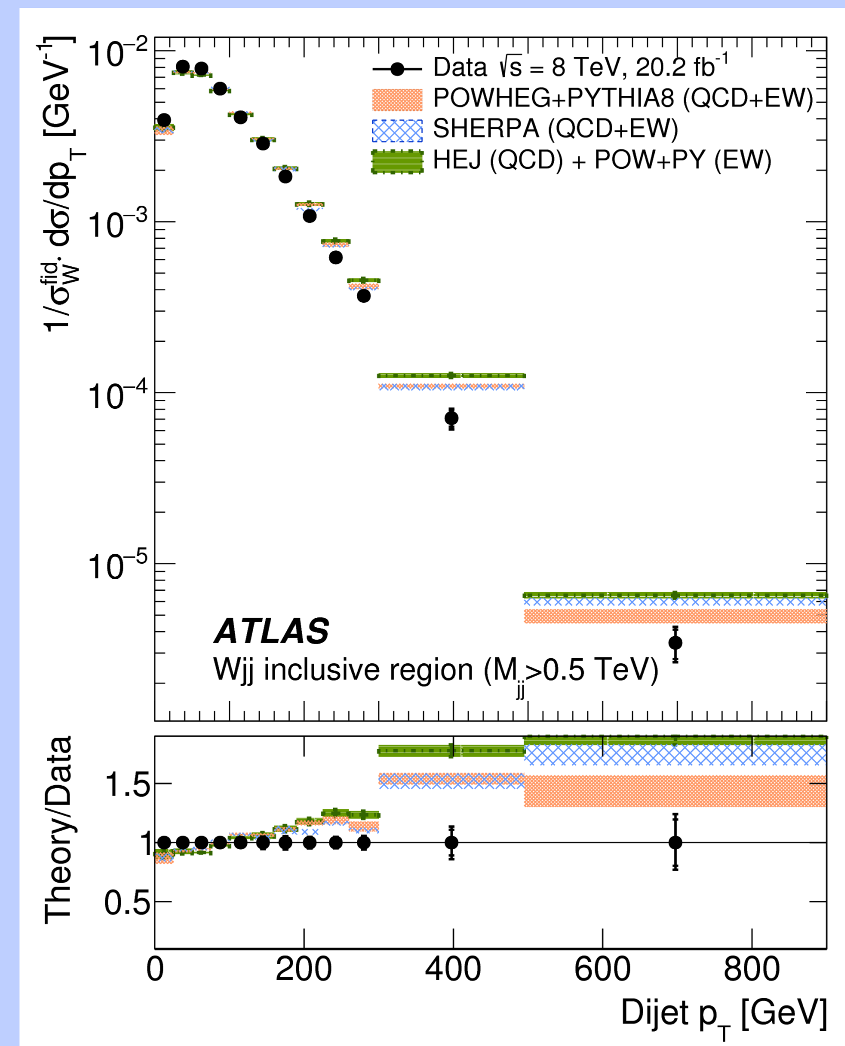
VBF W production @ 8 TeV

arXiv:1703.04362

Presence of EW Wjj clear in distributions of m_{jj} and jet rapidity separation
QCD+EW Wjj dijet p_T distribution not well modelled by MC



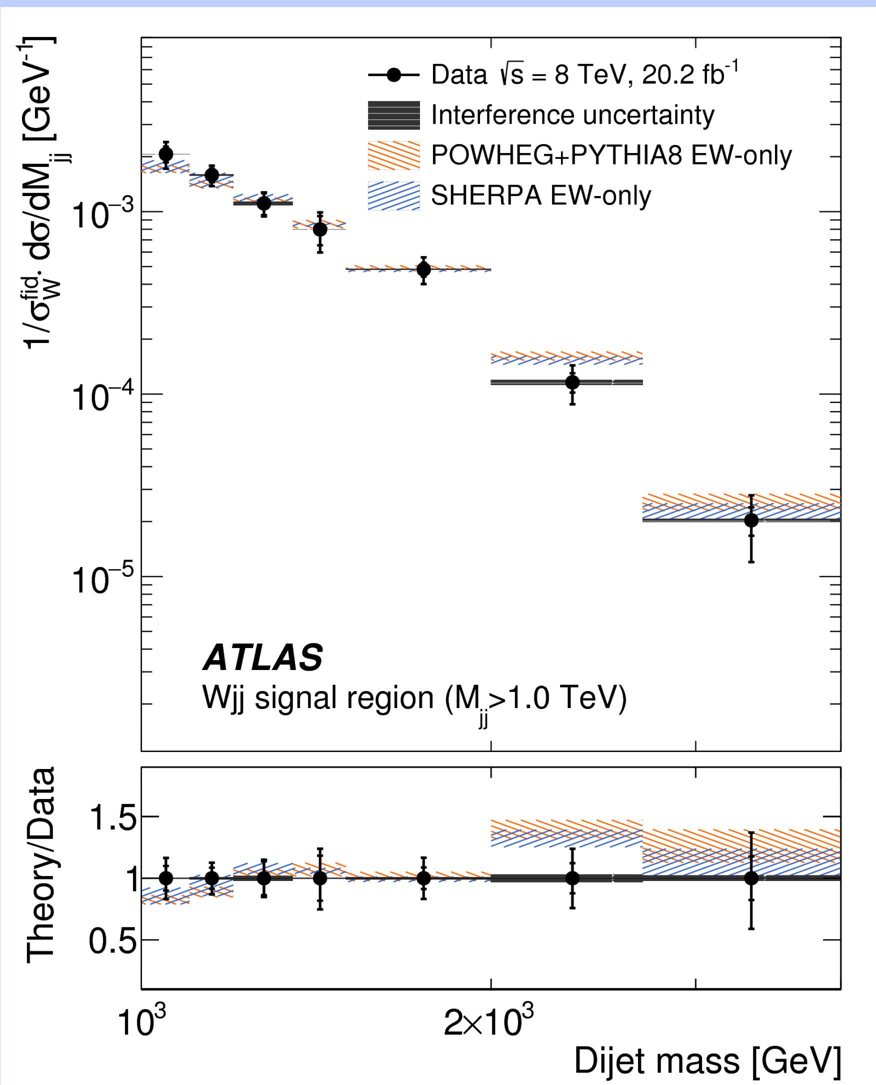


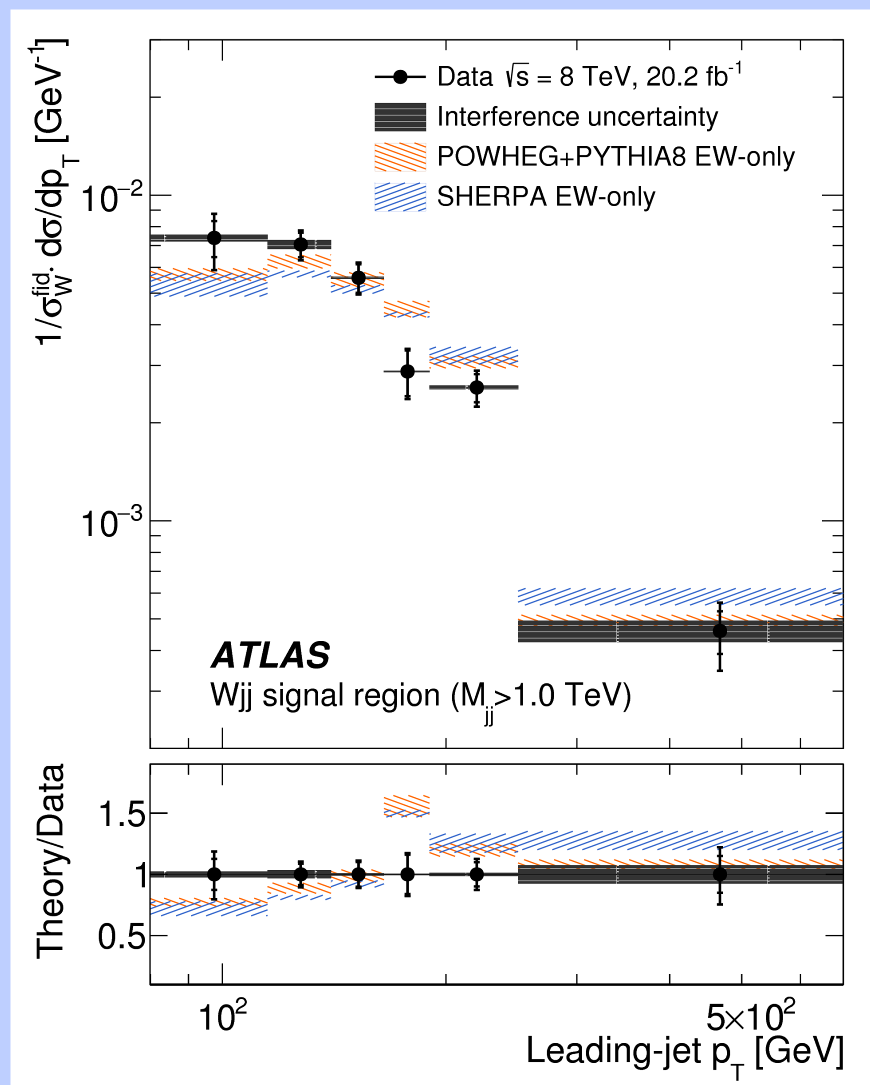


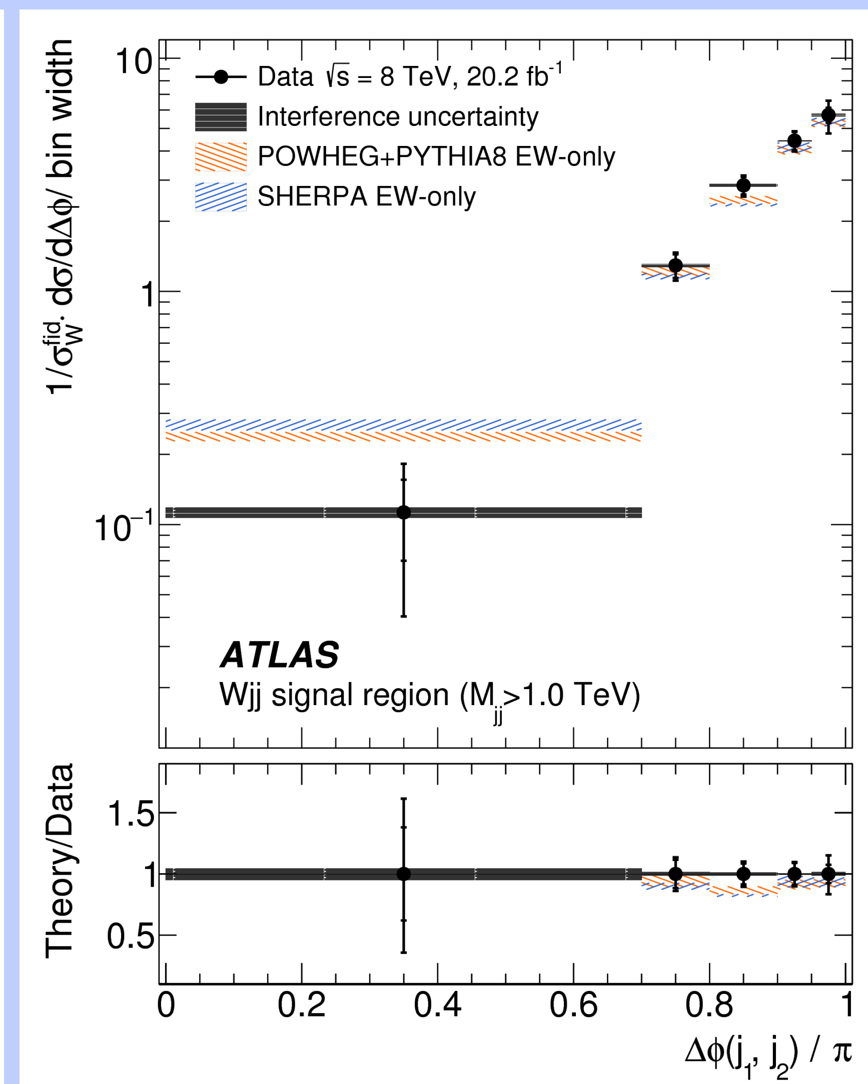
VBF W production @ 8 TeV

arXiv:1703.04362

Differential measurements of EW Wjj require $m_{jj} > 1$ TeV
Subtract QCD Wjj before unfolding data
Include distributions sensitive to anomalous gauge couplings





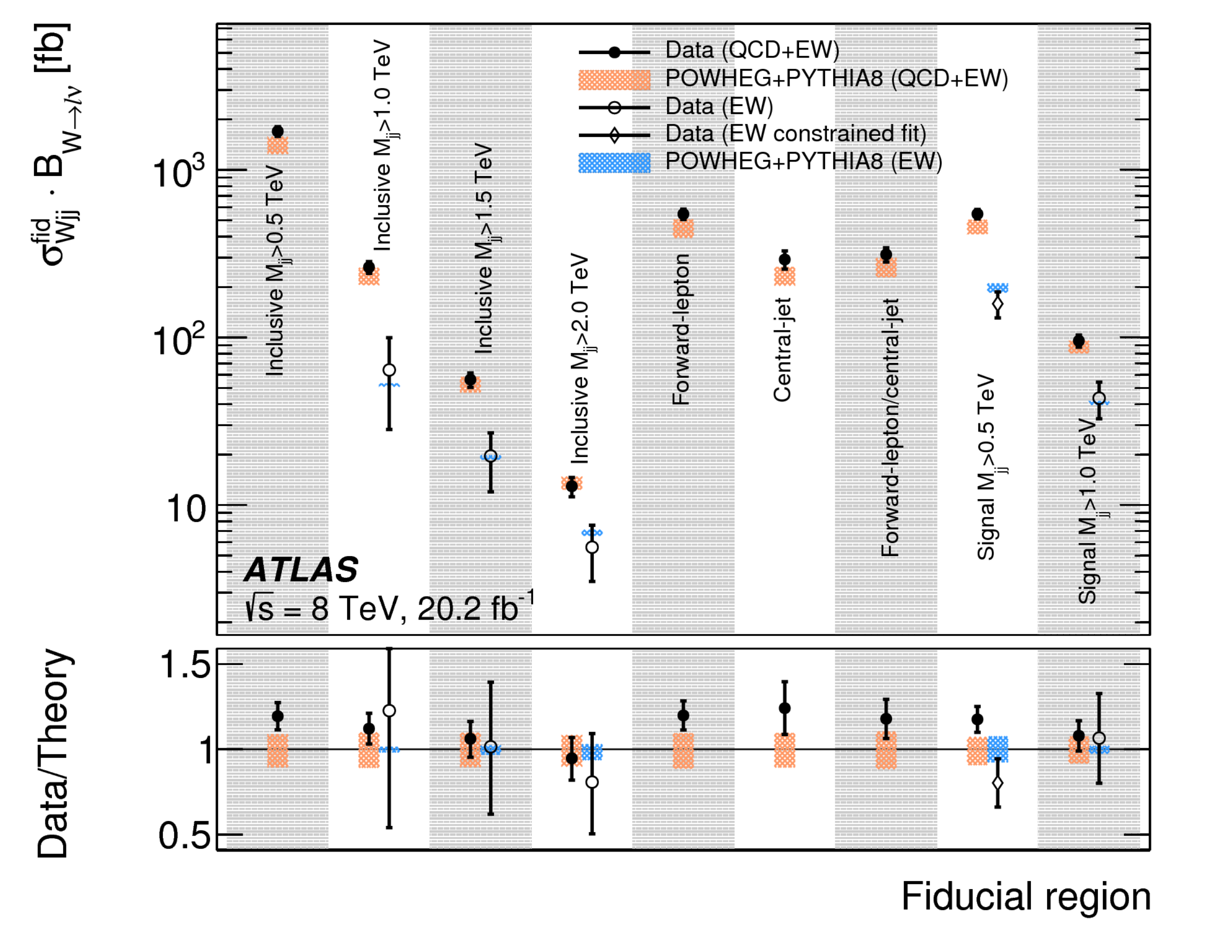


VBF W production @ 8 TeV

arXiv:1703.04362

Integrate measurements to obtain a range of fiducial cross sections

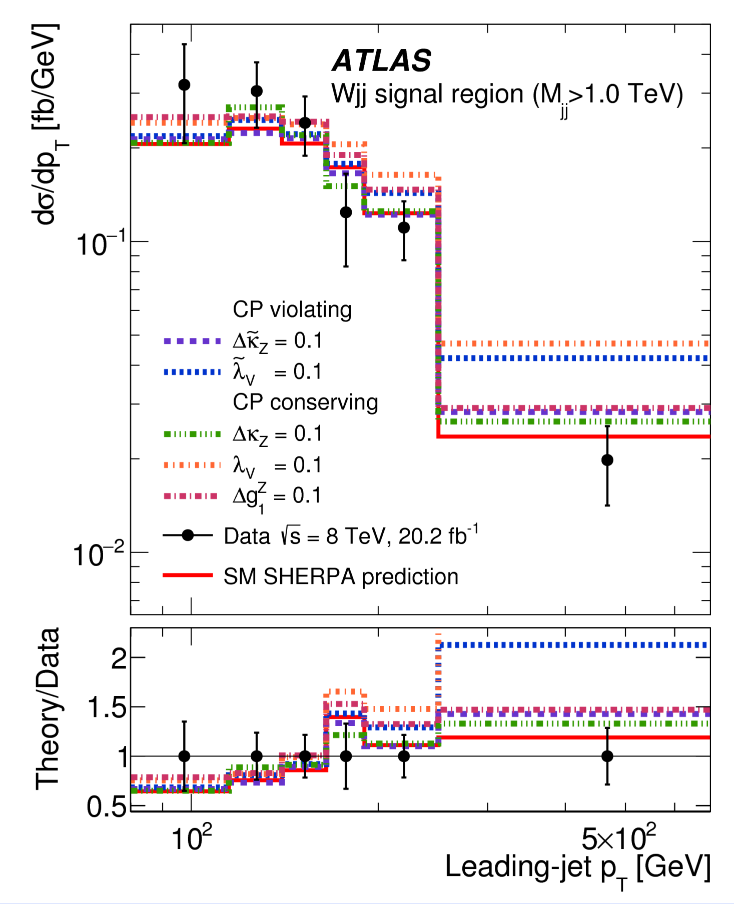
Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV
	Lepton $\lvert\eta\rvert < 2.5$
	$E_T^{miss} > 20$ GeV
	$m_T > 40$ GeV
	$p_T^{j_1} > 80$ GeV
	$p_T^{j_2} > 60$ GeV
	Jet $\lvert y\rvert < 4.4$
	$M_{jj} > 500$ GeV
	$\Delta y(j_1, j_2) > 2$
	$\Delta R(j, \ell) > 0.3$
Fiducial and differential 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



Fiducial region	$\sigma_{Wjj}^{fid} \times \mathcal{B}_{W\to\ell\nu}$ [fb]			
	QCD+EW		EW	
	Data	POWHEG + PYTHIA8	Data	POWHEG + PYTHIA8
Inclusive $M_{jj} > 0.5$ TeV	1700 ± 110	1420 ± 150	—	—
Inclusive $M_{jj} > 1.0$ TeV	263 ± 21	234 ± 26	64 ± 36	52 ± 1
Inclusive $M_{jj} > 1.5$ TeV	56 ± 5	53 ± 5	20 ± 8	19 ± 0.5
Inclusive $M_{jj} > 2.0$ TeV	13 ± 2	14 ± 1	5.6 ± 2.1	6.9 ± 0.2
Forward-lepton	545 ± 39	455 ± 51	—	—
Central-jet	292 ± 36	235 ± 28	—	—
Forward-lepton/central-jet	313 ± 30	265 ± 32	—	—
Signal $M_{jj} > 0.5$ TeV	546 ± 35	465 ± 39	159 ± 27	198 ± 12
Signal $M_{jj} > 1.0$ TeV	96 ± 8	89 ± 7	43 ± 11	41 ± 1

VBF W production @ 8 TeV

arXiv:1703.04362



Constrain triple-gauge couplings using region of high Q^2:

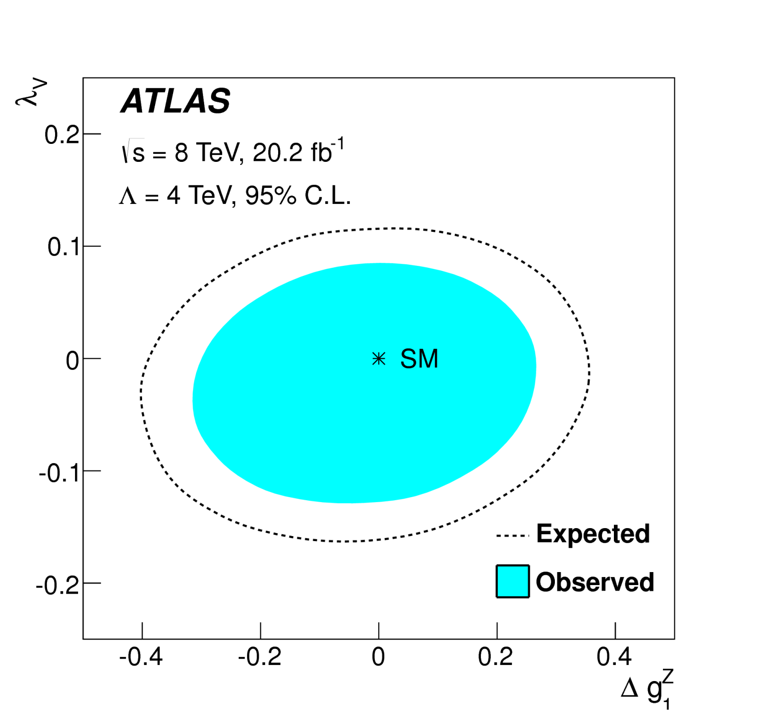
m_{jj}>1 TeV & leading jet p_T>600 GeV

39 events predicted, 30 events observed

Interpret using an effective Lagrangian to dimension 6:

$$i\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV}\Big\{\Big[g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^-\Big]$$

$$-\Big[\frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} + \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Big]\Big\},$$



And translate into an effective field theory: $\mathcal{L}_{\text{EFT}} = \sum_i \frac{c_i}{\Lambda^2} O_i,$

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}(g_1^Z - 1),$$

$$\frac{c_B}{\Lambda^2} = \frac{2}{\tan^2\theta_W m_Z^2}(g_1^Z - 1) - \frac{2}{\sin^2\theta_W m_Z^2}(\kappa_Z - 1),$$

$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_V,$$

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

$$\frac{c_{\tilde{W}WW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\tilde{\lambda}_V,$$

Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$\frac{c_W}{\Lambda^2}$	[−39, 37]	[−33, 30]
$\frac{c_B}{\Lambda^2}$	[−200, 190]	[−170, 160]
$\frac{c_{WWW}}{\Lambda^2}$	[−16, 13]	[−13, 9]
$\frac{c_{\tilde{W}}}{\Lambda^2}$	[−720, 720]	[−580, 580]
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	[−14, 14]	[−11, 11]

Summary

Extensive and detailed studies of VBF in W→lv and Z→ll production performed at ATLAS

Differential measurements of important backgrounds performed in both W & Z production

Fiducial measurements of EW Wjj & Zjj performed with 7 and 8 TeV data

Differential measurements of EW Wjj performed with 8 TeV data

Constraints set on triple gauge couplings