Recent VBF and VBS measurements in ATLAS

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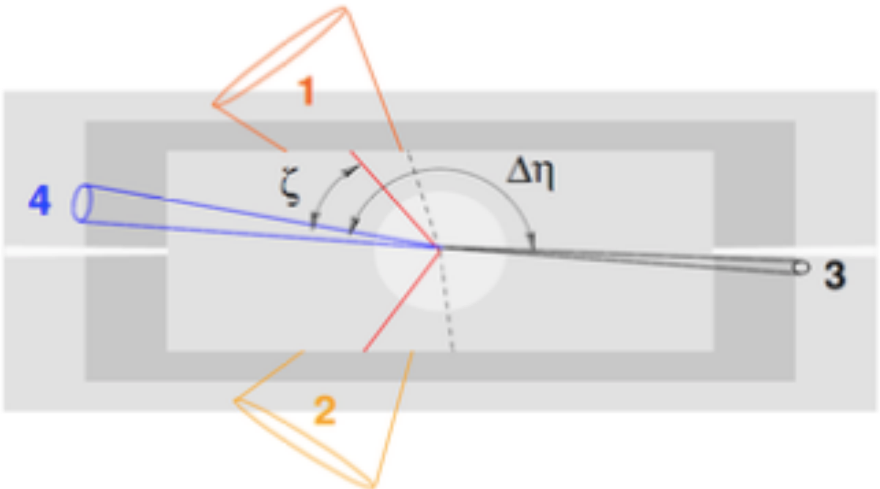
May 19th, 2017 - LHCP 2017 Conference - Shanghai

Introduction

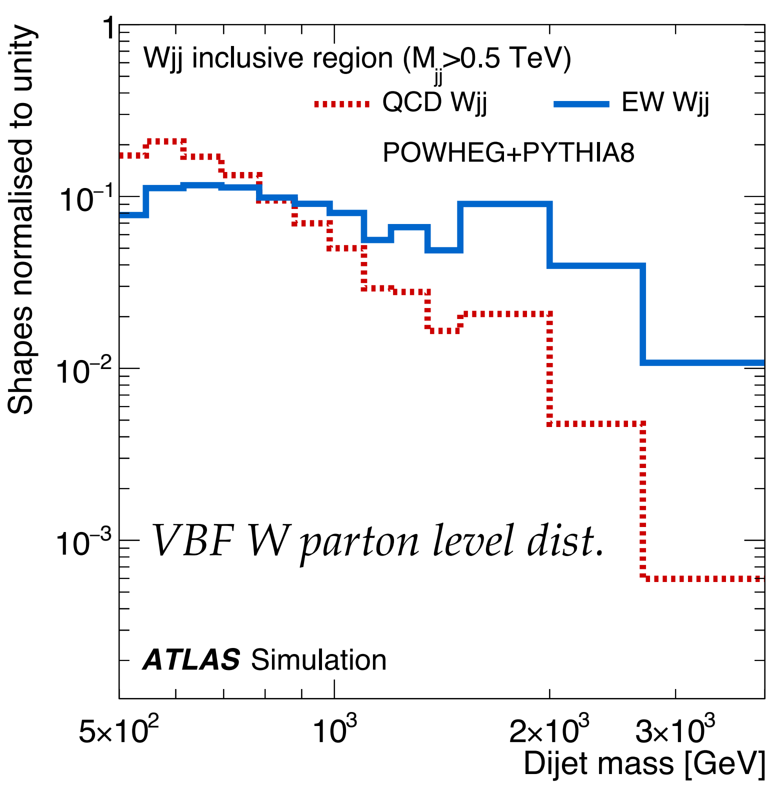
- After Higgs discovery 5 years ago, no deviation found in its properties
- **Vector Boson Fusion and Scattering (VBF/VBS) important test of electroweak sector and EW Symmetry Breaking**
  - Interaction with Higgs boson unitarizes the scattering amplitude -> is unitarization complete ?
  - **Complementary to Higgs boson property studies !**
- Yet no sign of new physics with direct searches
  - VBF/VBS allows indirect search by studying anomalous triple and quartic gauge couplings (aTGC, aQGC)
- VBF W and Z processes: interesting as candle for other VBF processes at LHC
- VBS : very low rate ($\mathcal{O}$(fb)) and large background
  - Main background is the QCD-induced production of gauge bosons, **scales as α^2_s / α^2**
  - VBS never observed until very recently ! (*see CMS talk by Philipp Pigard*)
- Leptons / photons generally used: clean channels, more limited backgrounds

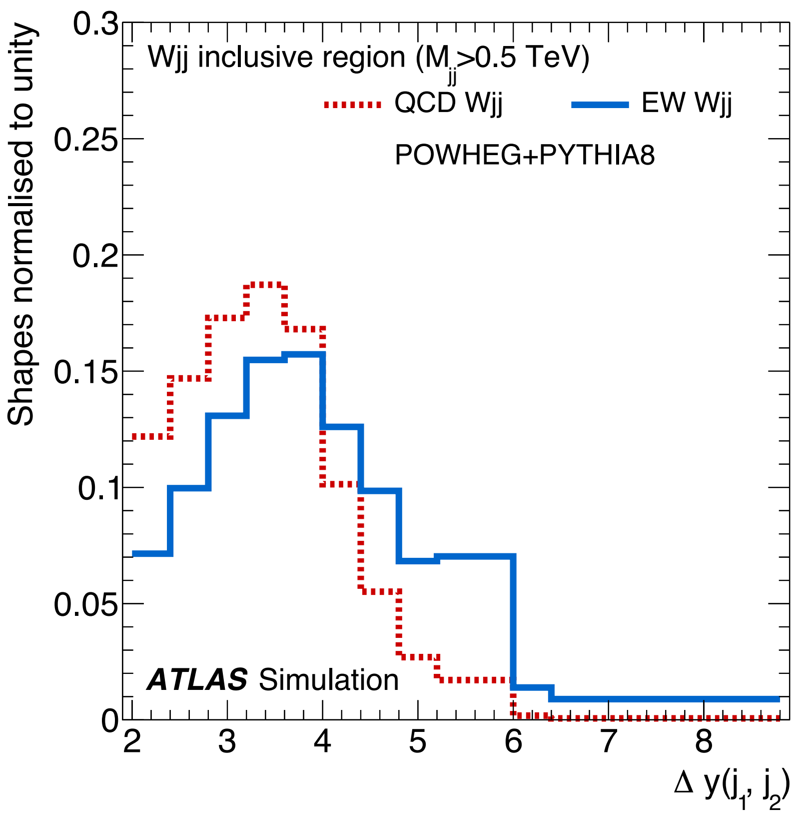
Phenomenology

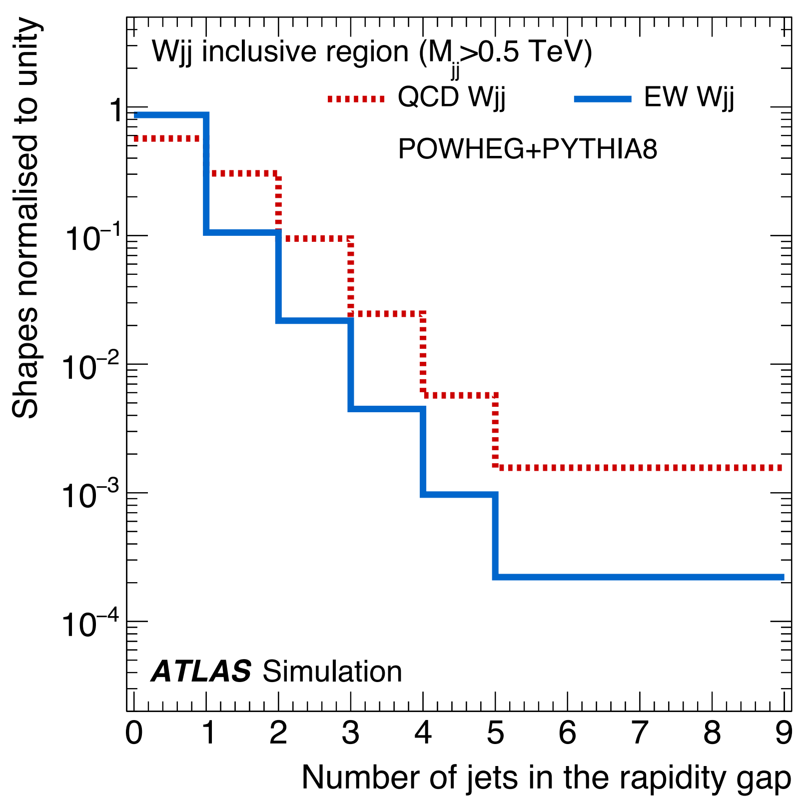
- **VBS/VBF: typical topology of final states**
  - Two hadronic jets in forward and backward regions with very high energy
  - Hadronic activity suppressed between the two jets (rapidity gap) due to absence of colour flow between interacting partons



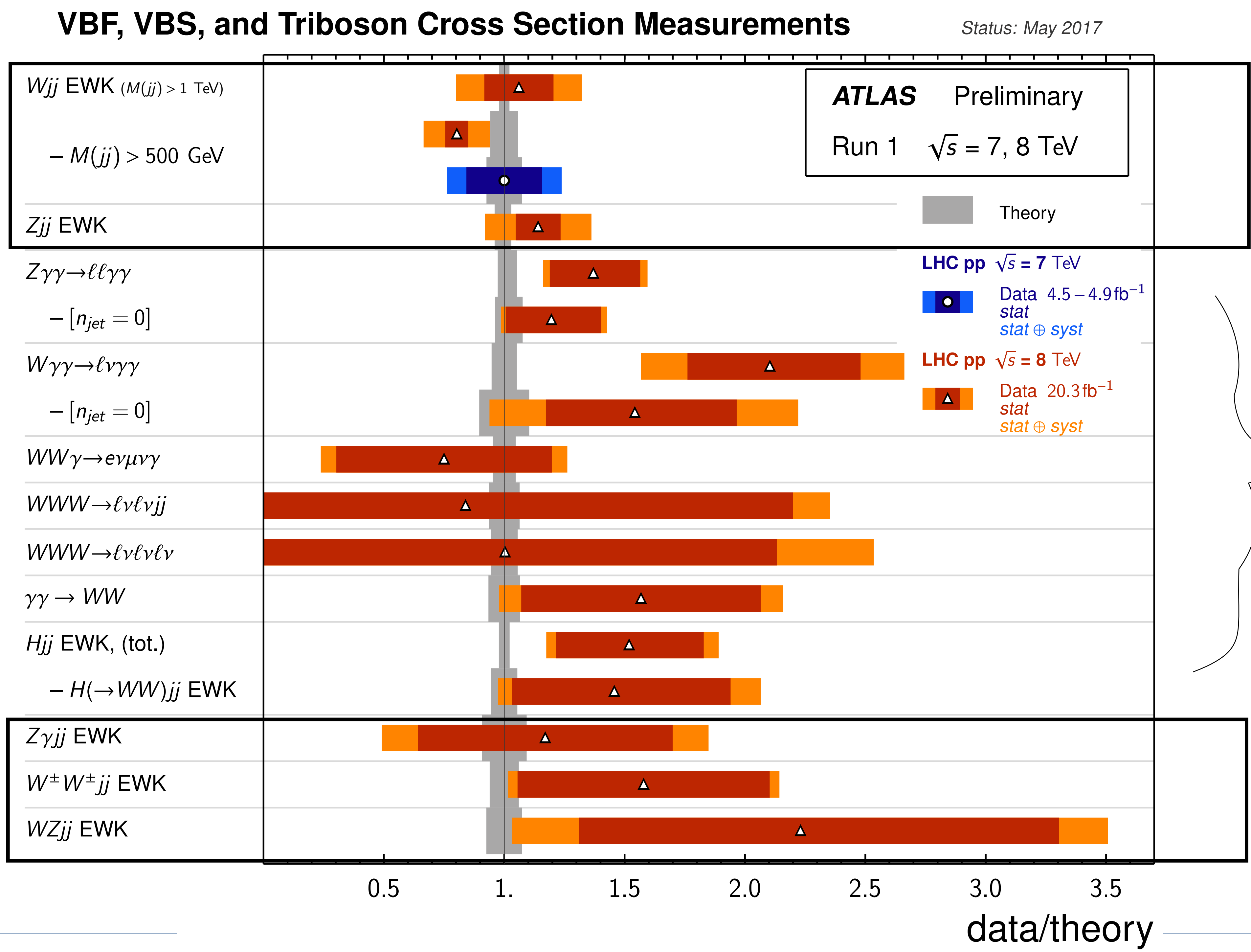
- Topological selection help reducing QCD background







Summary of ATLAS VBF/VBS measurements



VBF

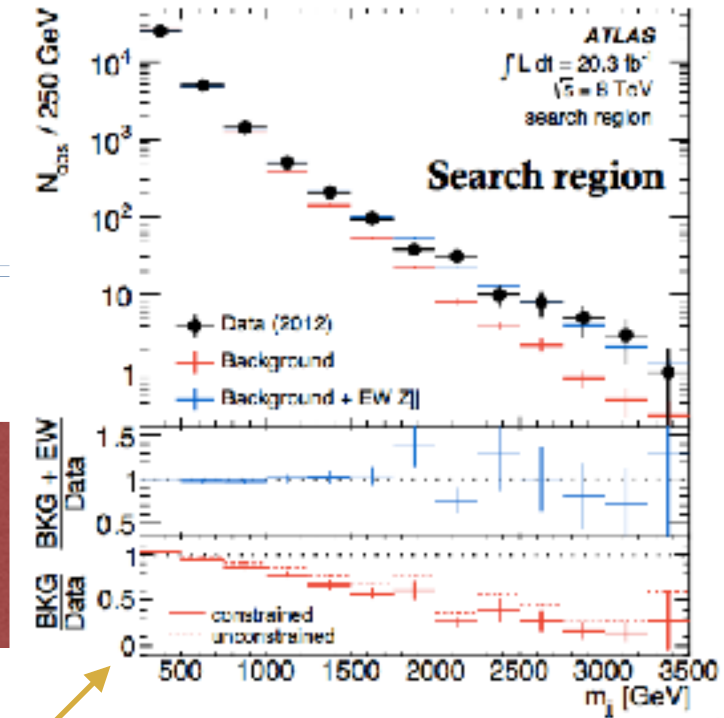
Tribosons covered in previous talk by Elena Yatsenko

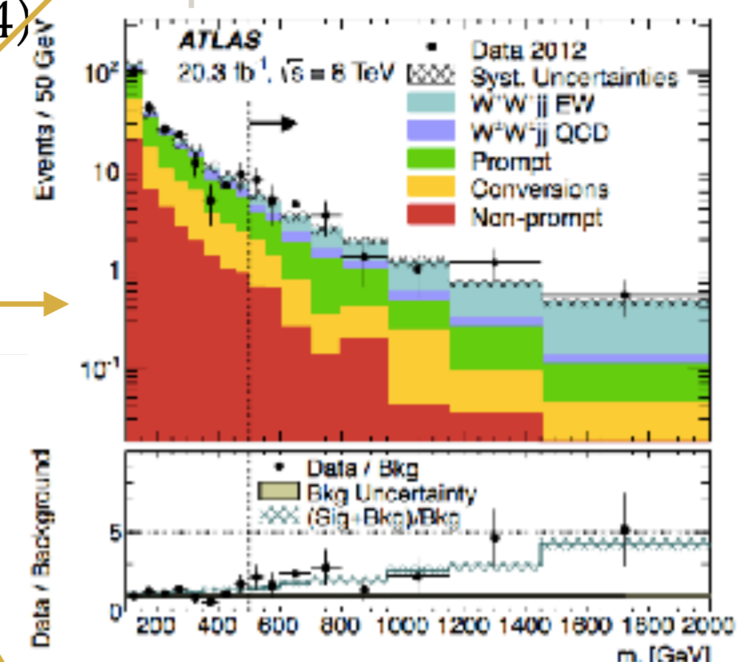
VBS

Summary of ATLAS VBF/VBS measurements

	Observed ?	Measurements
VBF Z @ 8 TeV *JHEP 04(2014)031*	**Yes, >5σ**	Inclusive and EW fiducial XS, differential XS (Powheg, Sherpa 1.4), aTGCs
VBS ssW @ 8 TeV *PRL 113, 141803 (2014), arXiv:1611.02428*	**No, 4.5σ**	EW fiducial XS, aQGCs
VBS WZ @ 8 TeV *PRD 93, 092004 (2016)*	**No, <2σ**	Upper limit EW XS, aQGCs
VBF W	NEW !	
VBS Zγ	NEW !	

data/theory

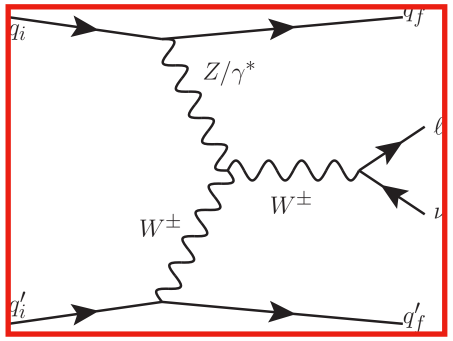




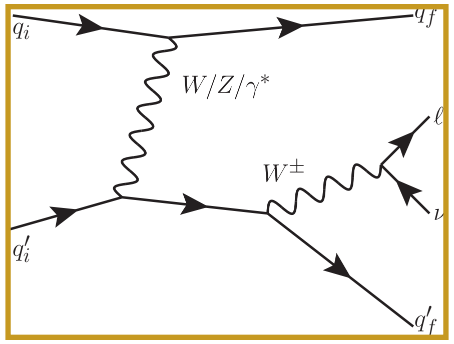
95% CL upper limit on $\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW}\to\ell'\nu\ell\ell}$ [fb]	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]
aQGC phase space		
Observed	0.25	0.25
Expected	0.13	0.13
$\pm1\sigma$ Expected	[0.08 ; 0.20]	[0.08 ; 0.20]
$\pm2\sigma$ Expected	[0.04 ; 0.28]	[0.06 ; 0.28]

VBF W

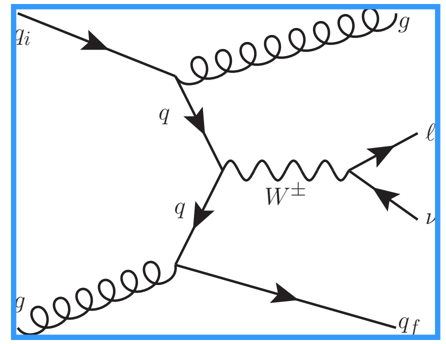
arXiv:1703.04362



VBF



EW non VBF

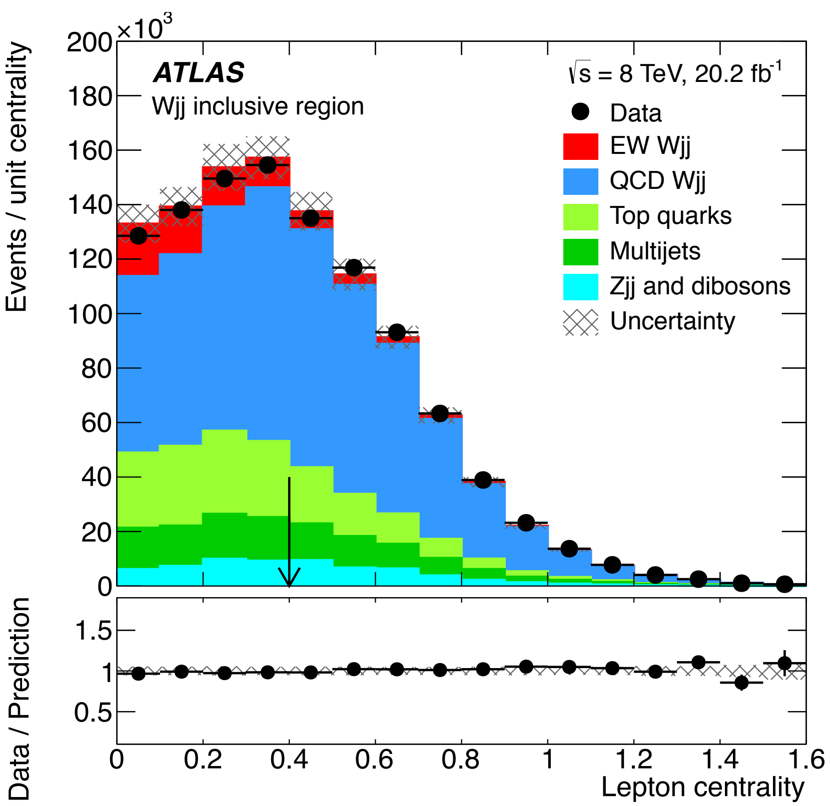


QCD
~10 x EW

- Dataset: 7 TeV (4.7 fb^{-1}), and 8 TeV (20.2 fb^{-1})

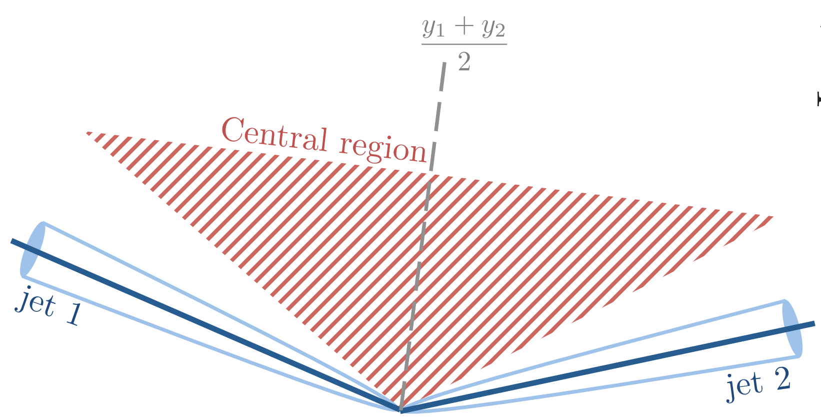
Inclusive selection:
- 1 lepton p_T>25 GeV,
- 2 jets with p_T>80/60 GeV,
- E_T^{miss}>20 GeV, m_T>40 GeV,
- **m_{jj}>500 GeV, $|\Delta Y_{jj}|$>2**

- **EW cross section**: build several regions to correct the QCD shape (and reduce unc.)
- **Main bkg**: top, Z+jets, dibosons (from MC) and multi-jets (data-driven)

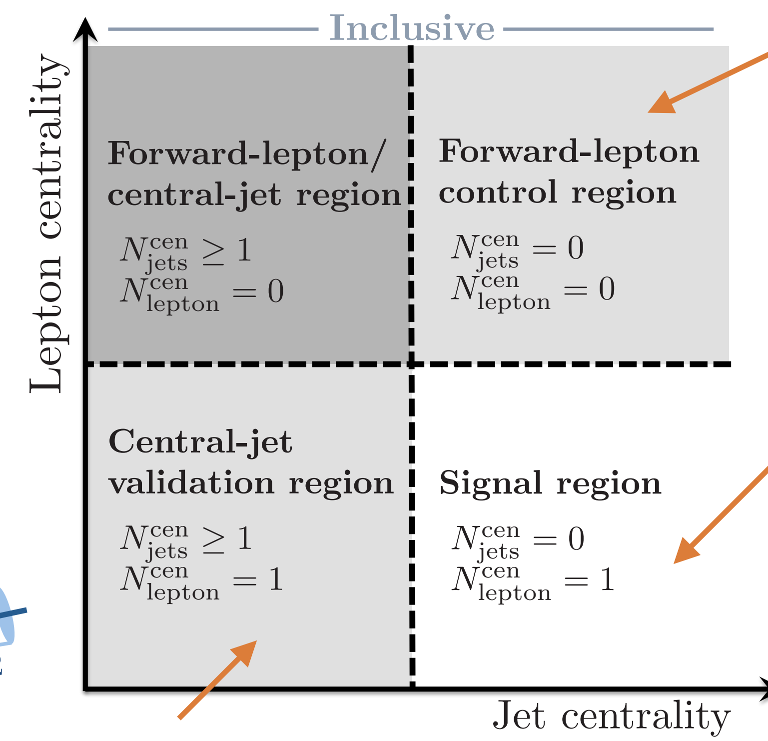


C=0.4 used to count the ℓ/j in the range

$$C_{\ell(j)} \equiv \left| \frac{y_{\ell(j)} - \frac{y_1+y_2}{2}}{y_1 - y_2} \right|$$



to derive correction (QCD-enhanced)

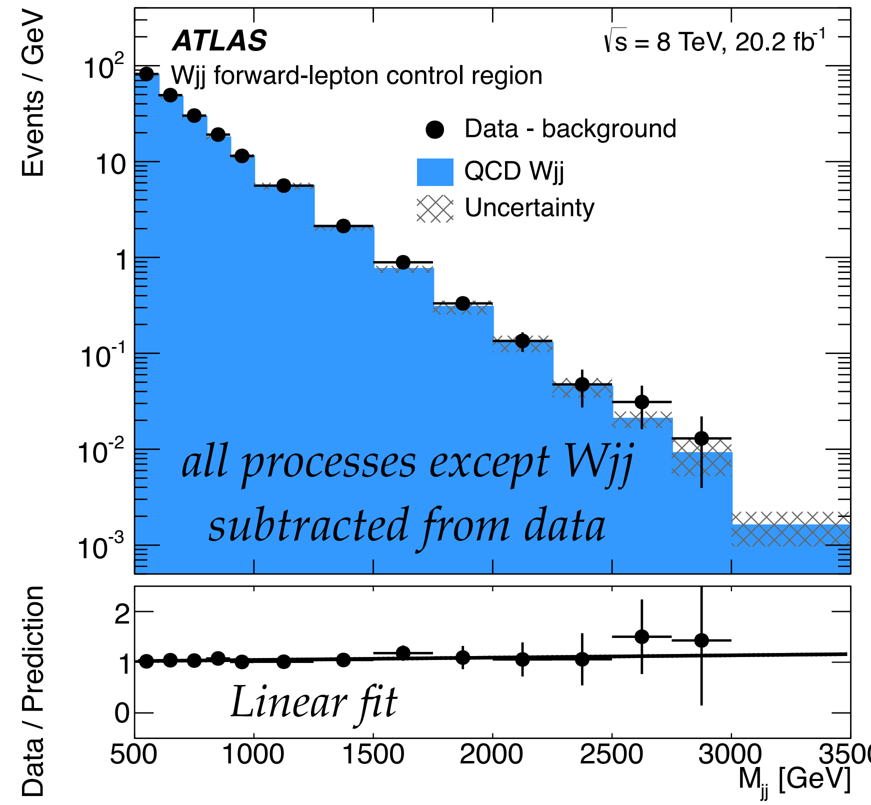


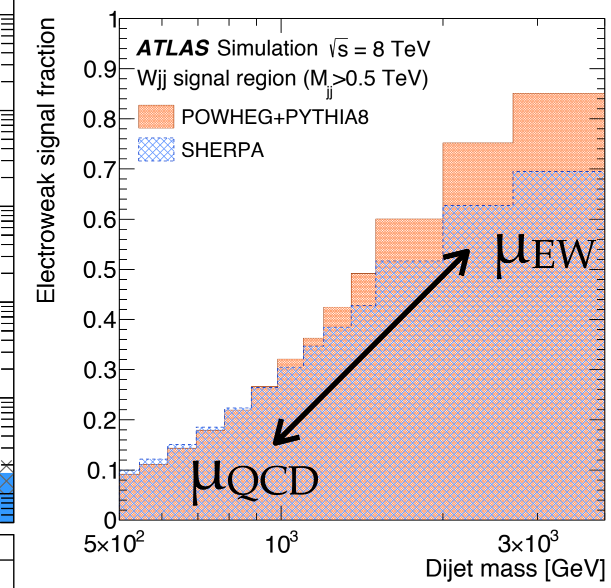
Apply correction and measure EW XS

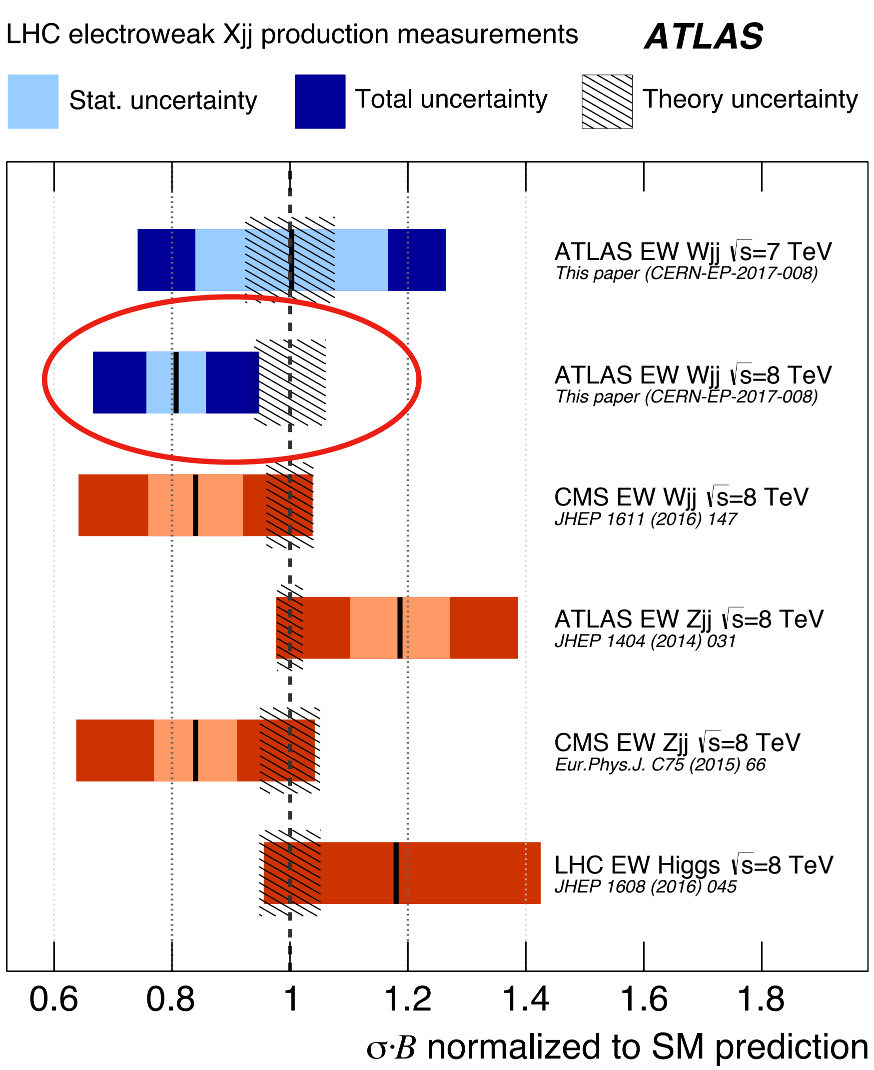
to validate correction (QCD-enhanced)

VBF W: EW fiducial cross section

- **Constraint on QCD m_{jj} shape**: linear fit of data / pred. (MiNLO Powheg+Pythia8) in CR
  - slope consistent with zero, but fit helps reducing total syst. unc.
- Binned likelihood fit of m_{jj} dist. for μ_{EW} **and** μ_{QCD}
- **Leading sys. unc.**: stat. unc. in CR and jet energy scale (JES) unc.
- **Observation with >5σ !**







Result of EW cross-section measurement:

$\sqrt{s}$	σ^{fid}_{meas} [fb]	σ^{fid}_{SM} [fb]	Acceptance $\mathcal{A}$	σ^{inc}_{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

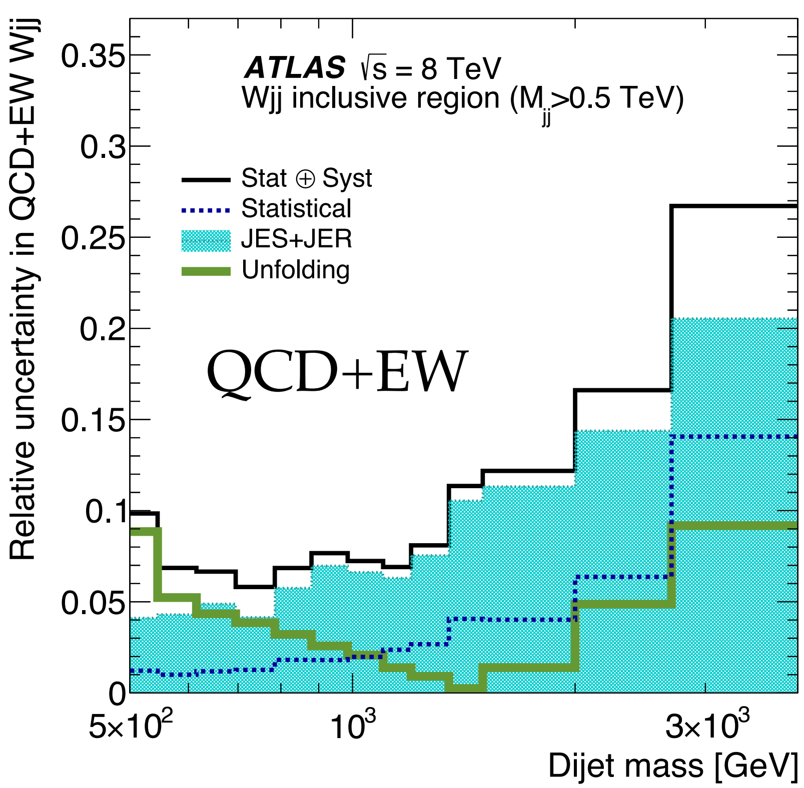
*with μ_{QCD} = **1.16 ± 0.04** (stat) @ 7 TeV, and **1.09 ± 0.02** (stat) @ 8 TeV*

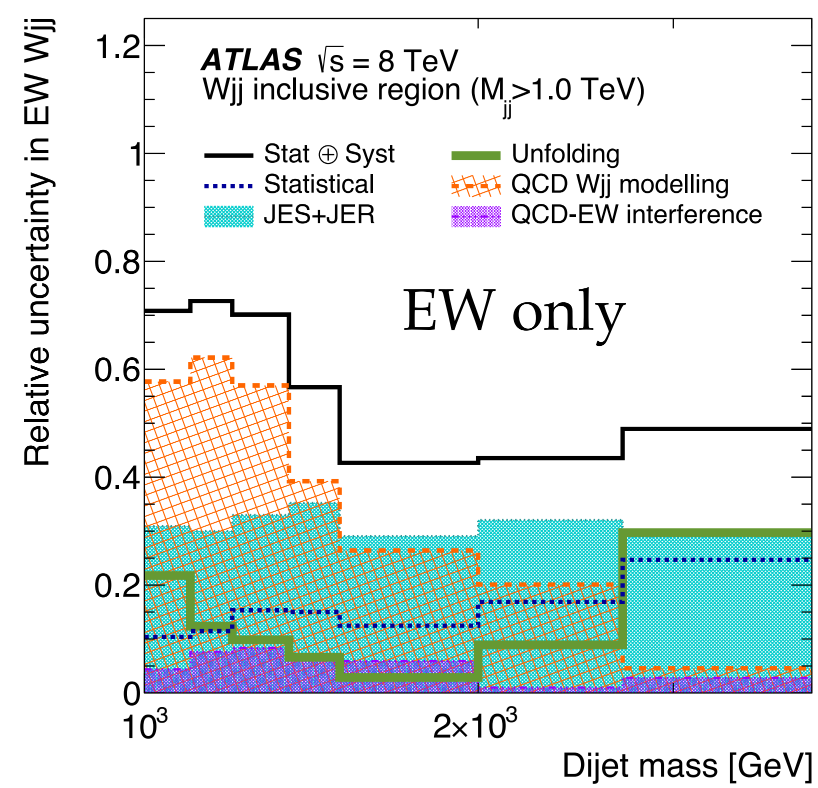
- 8 TeV measurement: **smallest relative uncertainty** among other VBF measurements at high m_{jj}.
- Good agreement with Powheg+Pythia8 (1.3σ deviation for 8TeV)

VBF W: differential cross sections

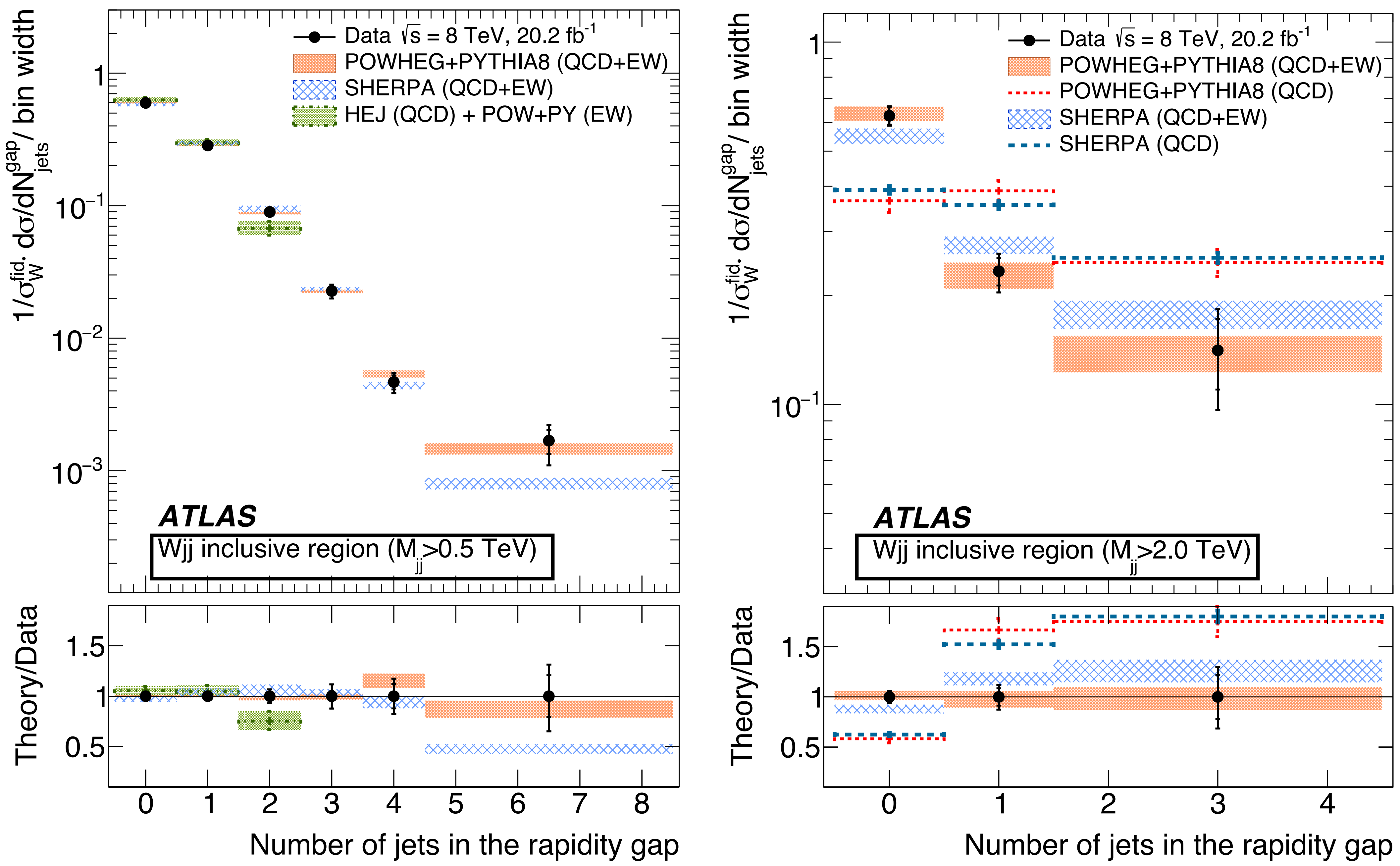
8 TeV data

- Combined QCD+EW in all regions ; EW only in regions with EW > 20%
- Bayesian iterative unfolding technique to correct for detector inefficiencies
- **8 variables studied:**
  - *Sensitive to EW production*: lepton and jet centrality (C_ℓ, C_j), m_{jj}, ΔY_{jj}, number of jets in gap; *Sensitive to anomalous coupling*: p_{Tj1}, p_{Tjj}; *Sensitive to CP-violating coupling*: $\Delta\phi_{jj}$
- **9 regions:**
  - 4 regions defined in previous slide + inclusive + m_{jj}>1,1.5,2 TeV, SR + m_{jj}>1 TeV (40% EW)
- **Leading systematics:**

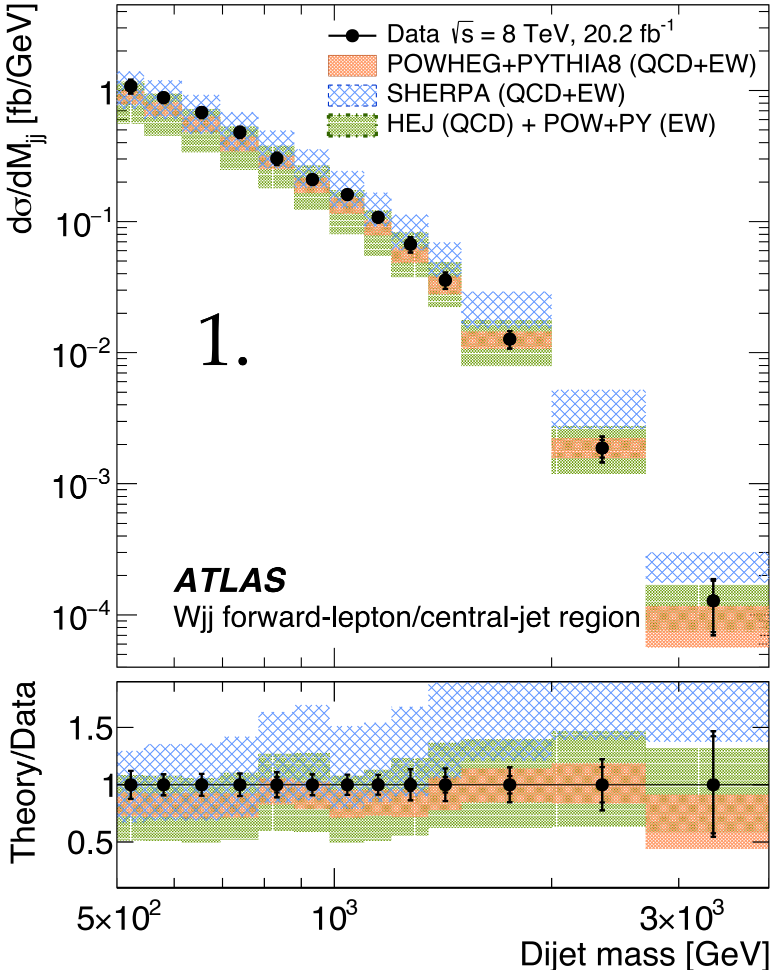


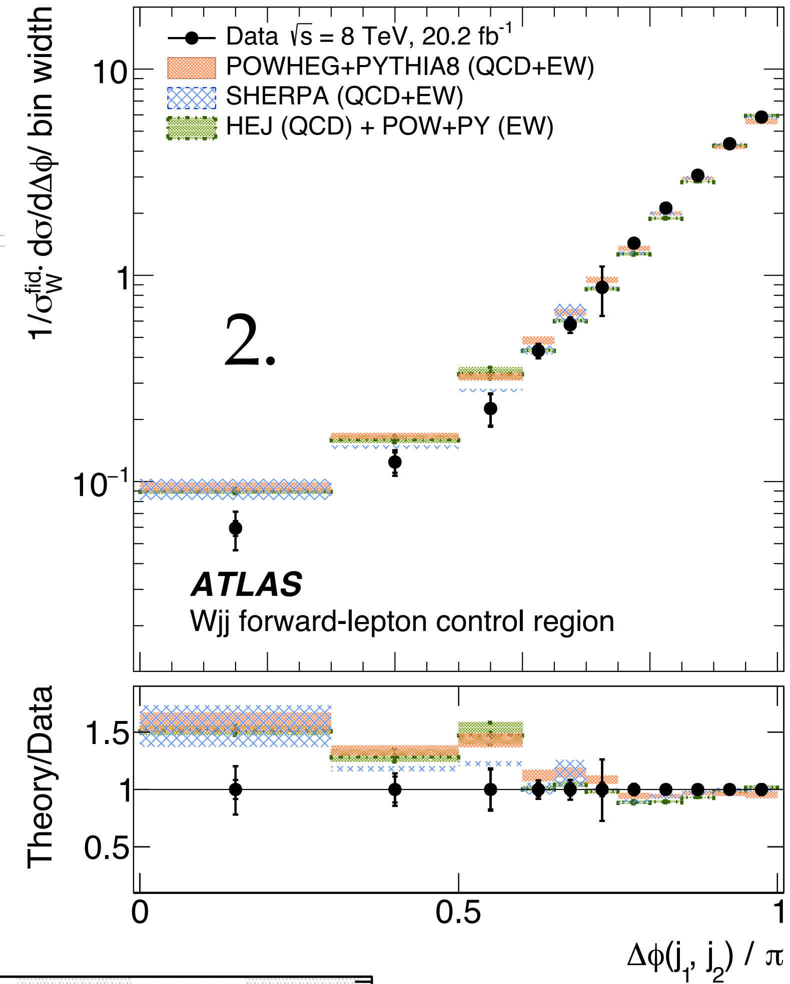


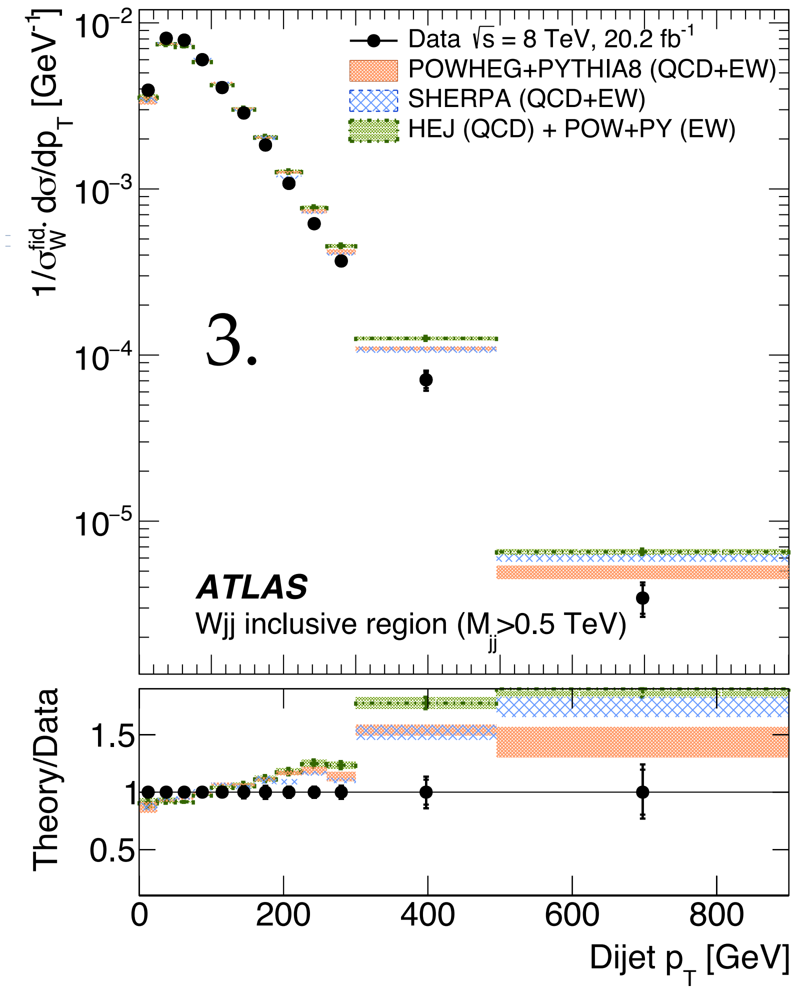
Number of jets in rapidity gap

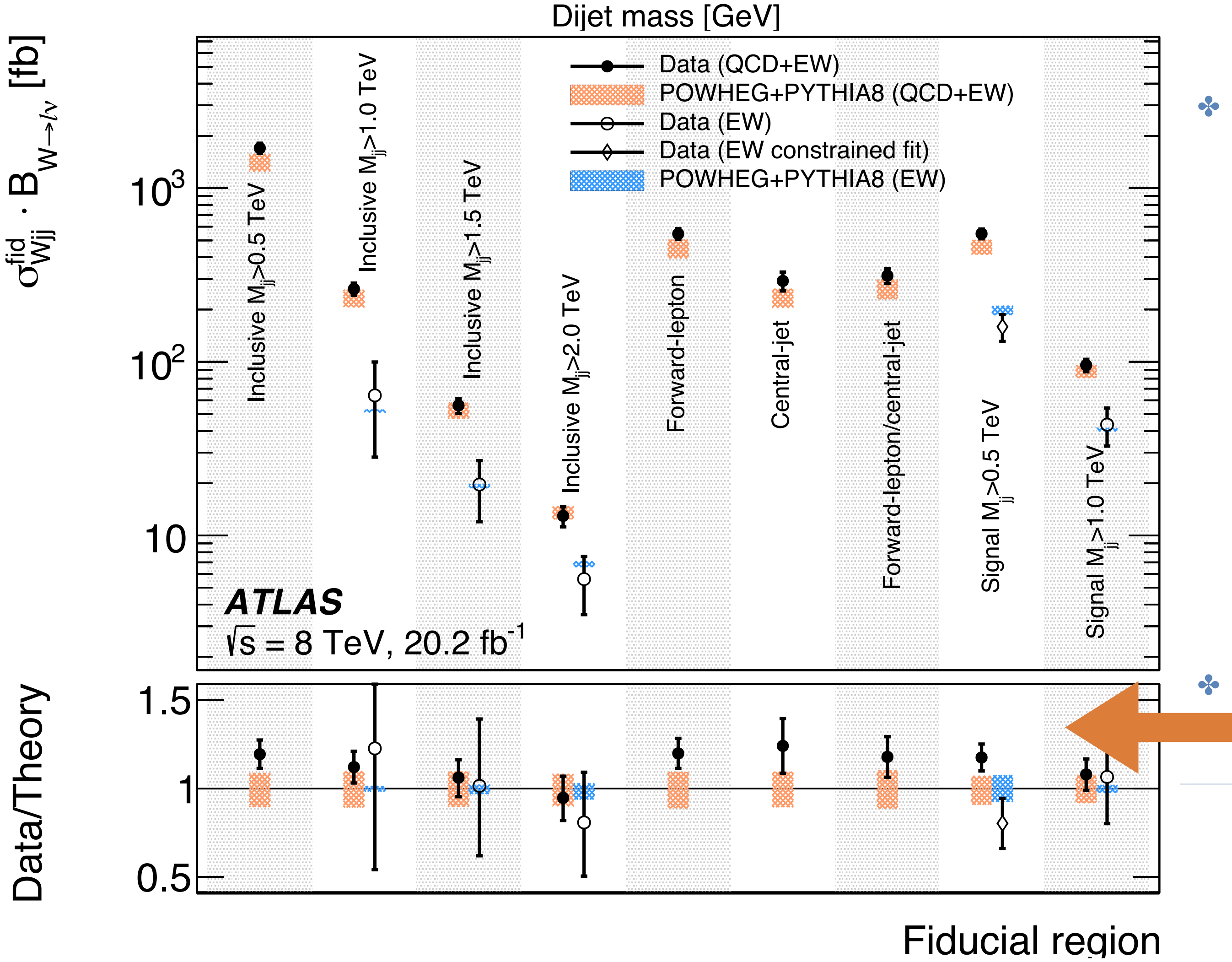


- In region m_{jj}>2 TeV, EW contribution becomes visible
- Comparison to 3 generators: Powheg-Pythia (NLO), Sherpa 1.4 (LO) and HEJ (all-order re-summation calculation, only for QCD-enhanced regions)
- **Sherpa does not model well the shape of distribution**



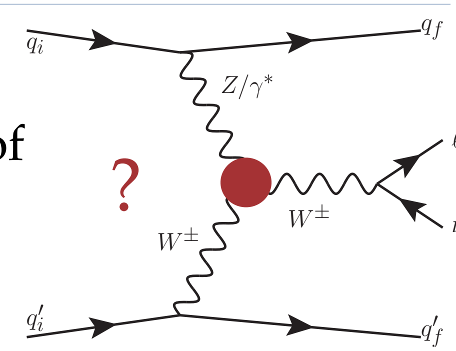






- **Data overall well described by the 3 generators in all variables and regions. However:**
  1. **m_{jj}**: Sherpa higher at high m_{jj} and larger disagreement in shape with data than Powheg+Pythia8 or HEJ
  2. **Δϕ**: Pred. overestimate rate at small angles in all regions
  3. **pT_{jj}**: Pred. overestimate rate at high pT_{jj} in inclusive and signal-enhanced regions, but not in central-jet validation region. Seems to be related to modelling of QCD $W j j$. (due to NLO EW corrections ? arXiv: 1511.08692)
- **Integrated XS**: ~15–20% higher than prediction in fiducial regions dominated by QCD

VBF W: limits on aTGCs



- Probed in signal region + m_{jj}> 1 TeV ; pT_{j1}>600 GeV
- Complementary to dibosons (*s*-channel exchange instead of *t*-channel)
- Sensitive to WWZ and WWγ couplings
- Effective lagrangian + form factors introduced to preserve unitarity

= 1 in SM

= 0 in SM

$$iL_{\rm eff}^{WWV} = g_{WWV}\left\{\left[g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}\right]\right.$$
$$\left. - \left[\frac{\tilde\kappa_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} + \frac{\tilde\lambda_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\right]\right\},$$

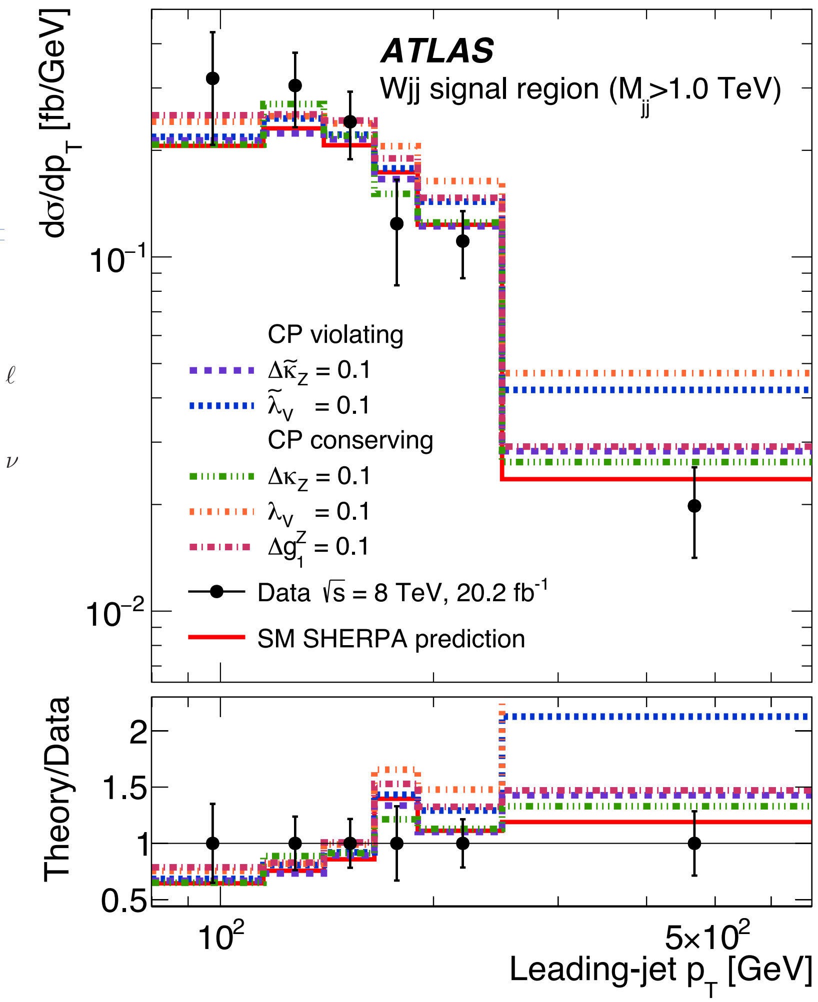
CP violating

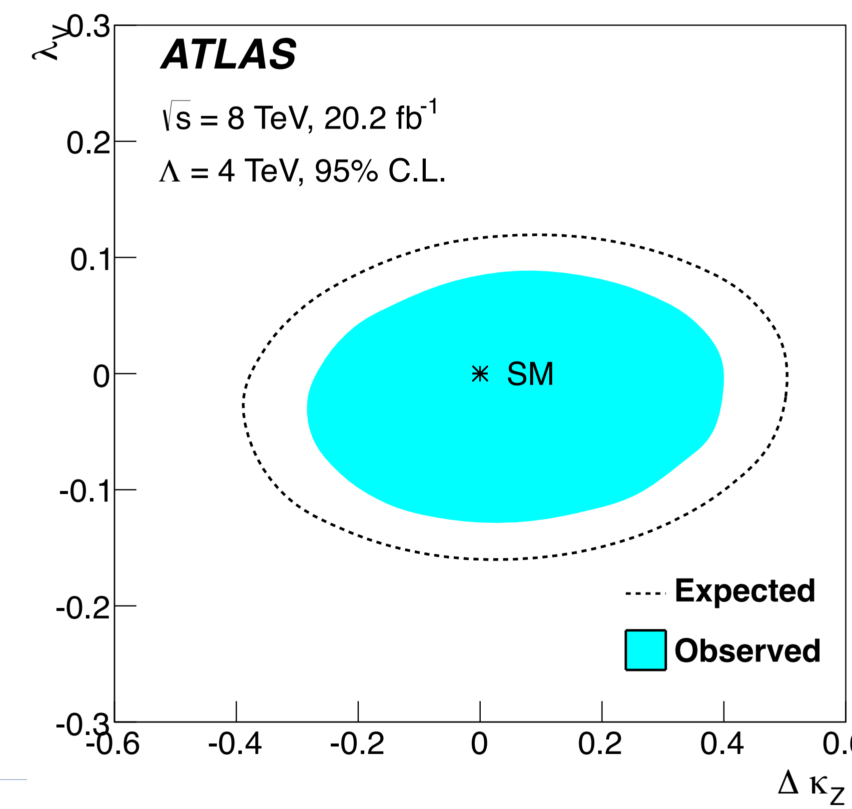
= 0 in SM

- 95% confidence-level intervals are set for unitarization scale of Λ = 4 TeV
  - **λ_V intervals competitive with WW ones**

8 TeV data

	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]



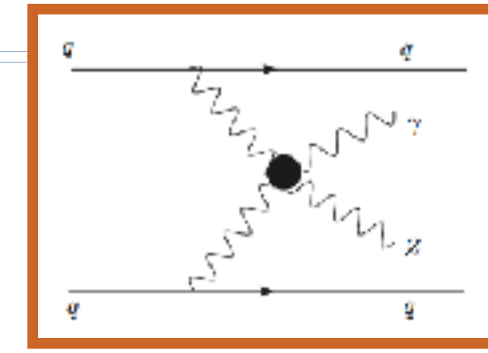


VBS Zγ + 2j

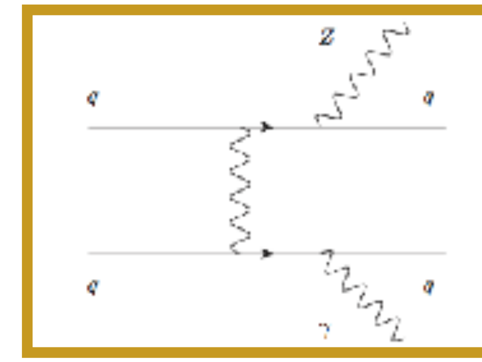
arXiv:1705.01966

- **Goals**:
  - Measurement of total Zγjj cross section, and probing VBS with Z->ee/μμ
  - Setting limits on aQGC with Z->ee/μμ/νν
- **Interests:**
  - Z->ee/μμ clean channels, relatively small background
  - Using 3 decay channels, stringent limits on FT8 and FT9 EFT operators
  - **But challenging**: small cross section and very large QCD production

VBS

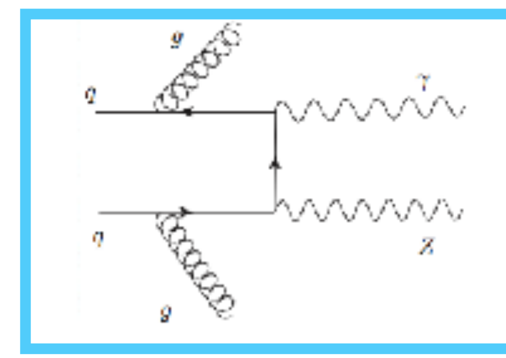


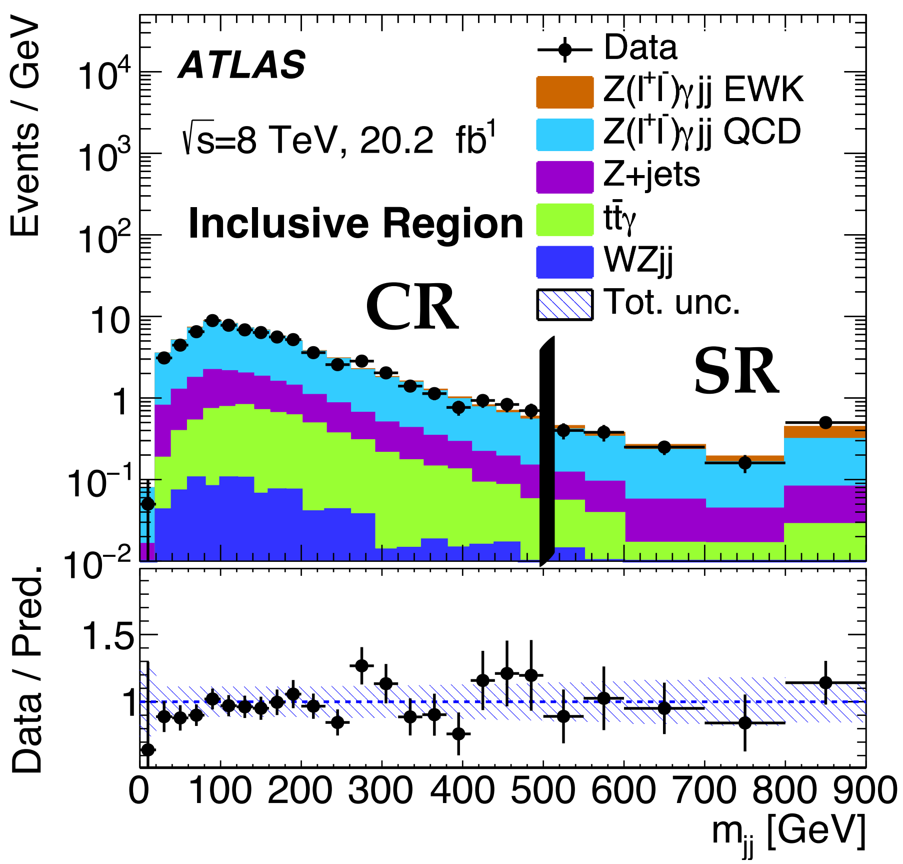
EW non VBS



QCD

Dominant background





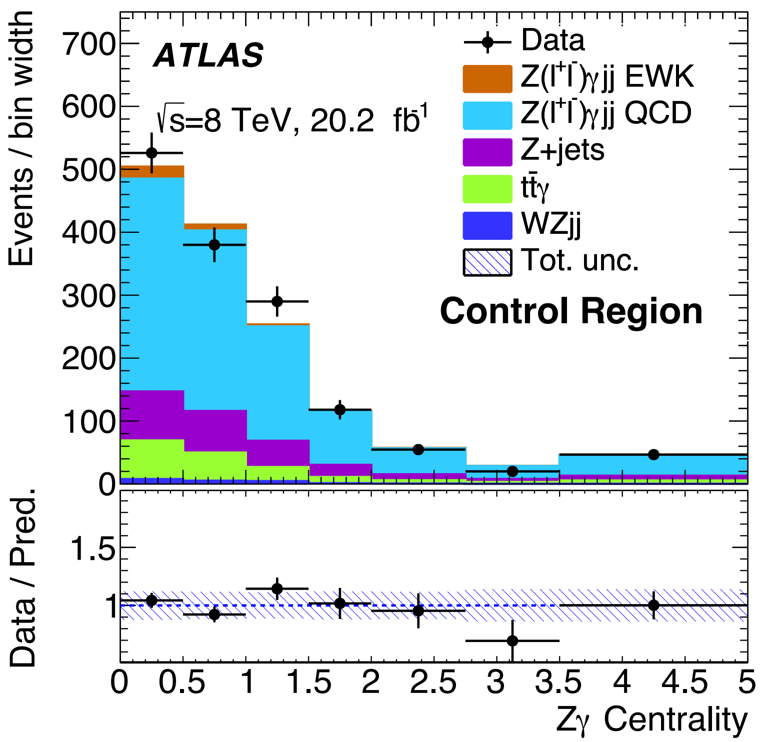
Inclusive $\ell^+\ell^-\gamma$ selection:
- 2 leptons p_T>25 GeV, 1γ p_T>15 GeV
- 2 jets with p_T>30 GeV,
- $m_{\ell\ell}$> 40 GeV, ($\ell\ell + \ell\ell\gamma$) >182 (remove FSR γ)

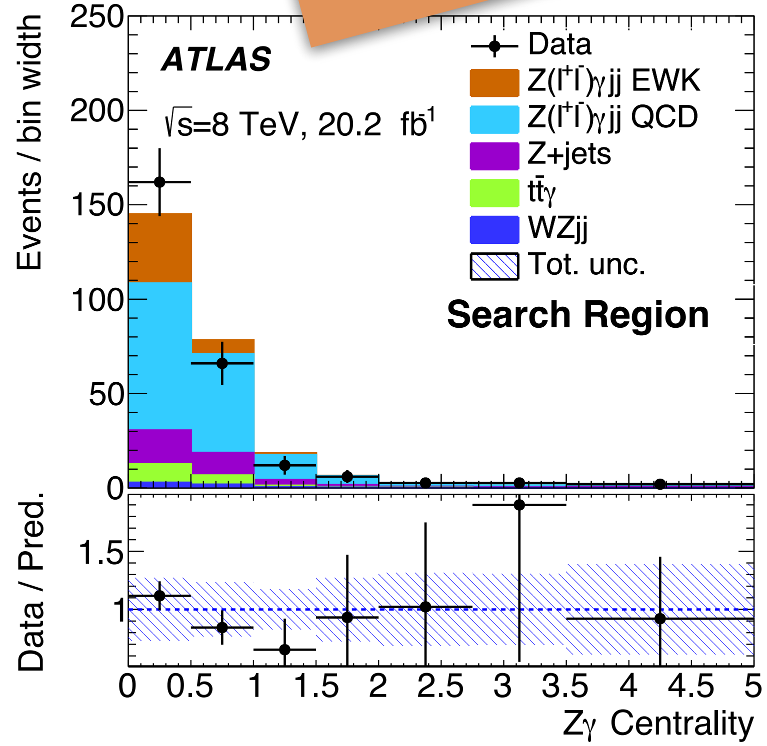
- ***ℓ+ℓ-* channel : 4 regions**
  - **Inclusive region :** for checks
  - **Control region**: 150<m_{jj}<500 GeV (constrain QCD norm, <5% of signal)
  - **Search region**: m_{jj} > 500 GeV (VBS enhanced, >20%) ; N_{exp}=22.8 +/- 1.5
  - **aQGC region** : SR + pT_{γ} > 250 GeV ; N_{exp} = 0.41 +/- 0.04

Data used: 8 TeV data, 20.2 fb-1

VBS Zγ + 2j

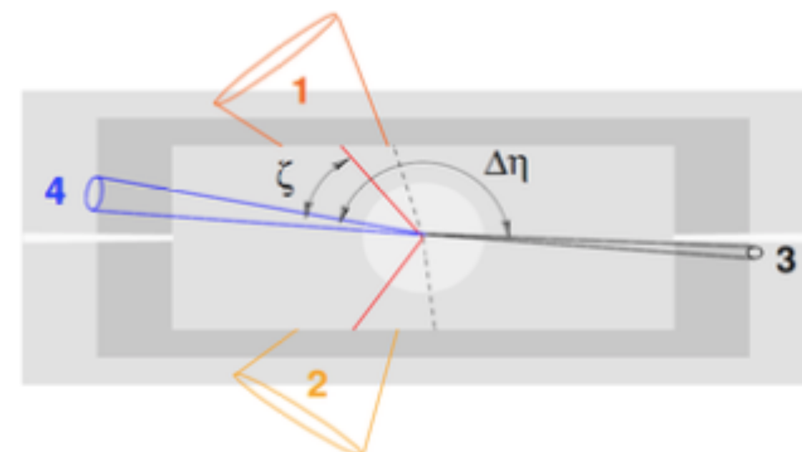
Good description of data by LO Sherpa v1.4.5





Centrality:

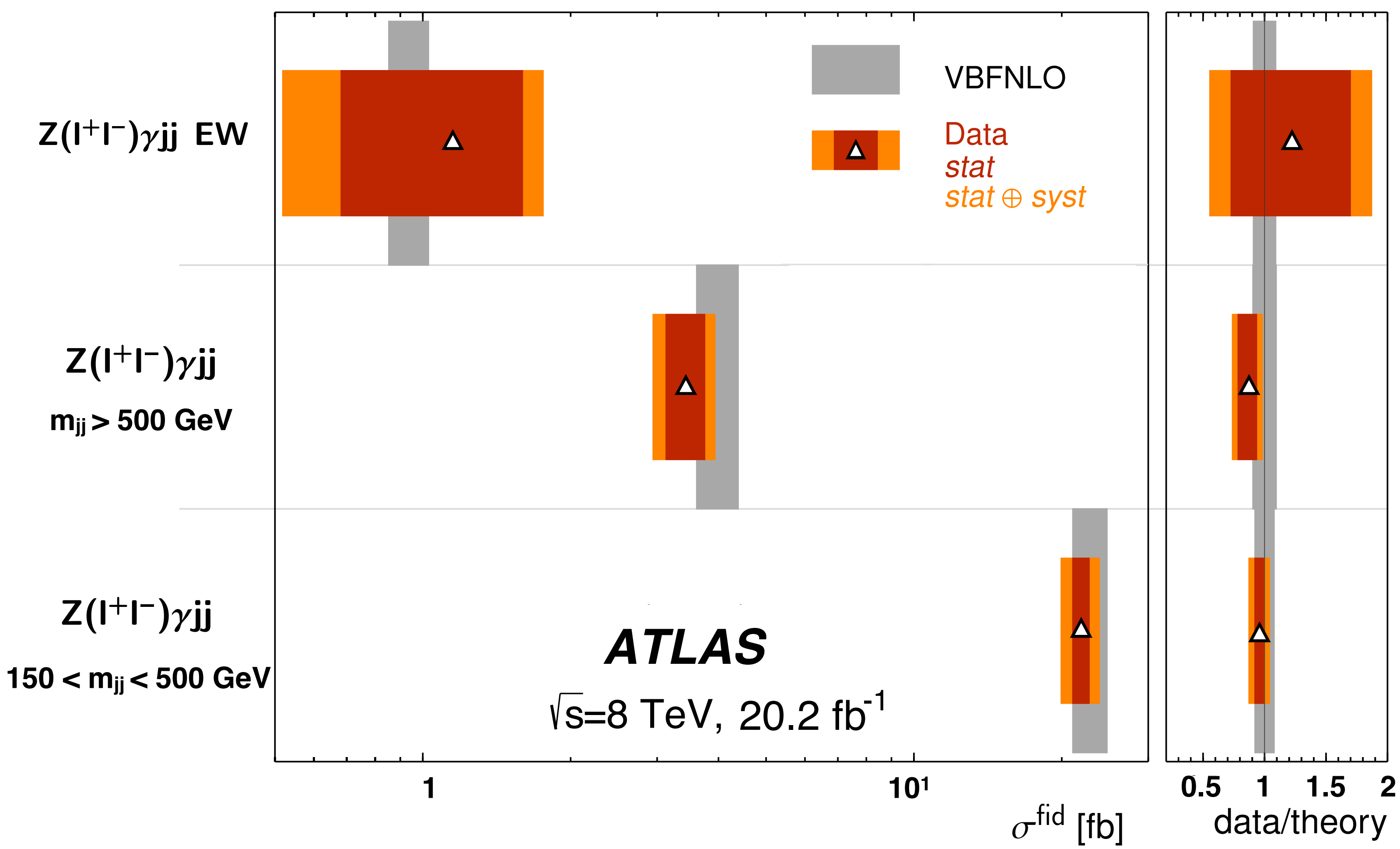
$$\zeta \equiv \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2},$$



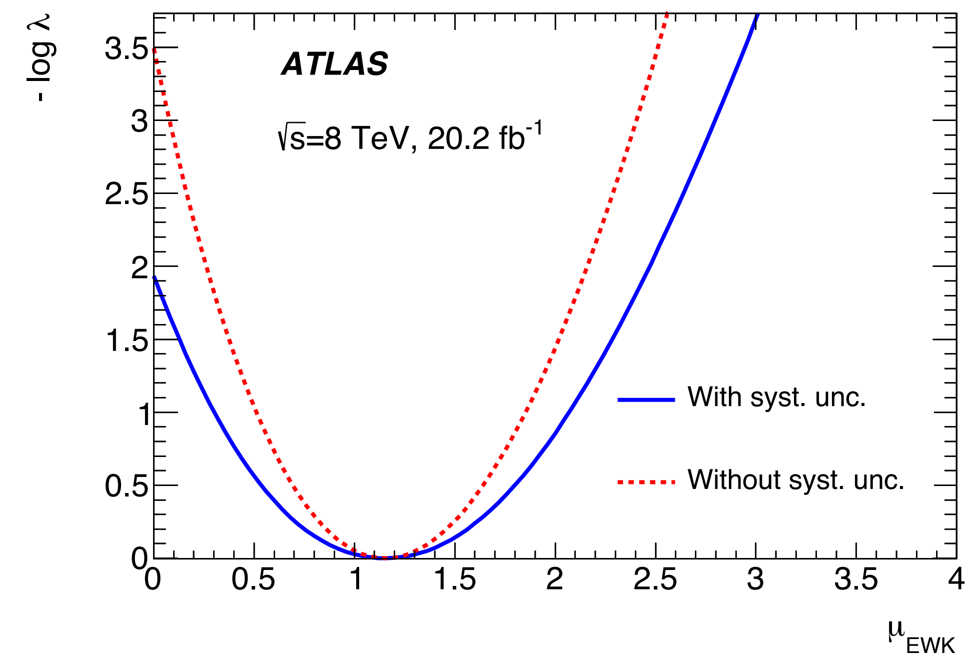
- **Centrality variable used to perform XS measurement in ℓ+ℓ- channel**
- Zγjj QCD:
  - shape taken from Sherpa v1.4 MC
  - normalisation extracted fitting simultaneously CR and SR for EW studies (QCD scaling factor = unconstrained nuisance parameter in fit)
- **Main Zγjj reducible backgrounds:**
  - Z+jets -> 2D sideband data-driven method -> ~23% of Zγjj events
  - ttbarγ ->MadGraph5_AMC@NLO v5.2, XS @ NLO
- Electron and muons channels combined

VBS Zγ + 2j: cross sections

- **Cross section measurements:**
  - Extended binned likelihood fit over Zγ centrality variable with parameter of interest $\mu = \sigma_{data} / \sigma_{MC}$
  - Measurement of total (in SR and CR) and EW-only (in SR) XS
  - Measurements compared with **VBFNLO v2.7.1** (4-10% unc.)



Excellent agreement with VBFNLO
Large statistical (~40%) and systematic (~50%) uncertainties



- **Significance for observing the EW signal: 2.0σ (1.8σ expected)**
- **Upper limit on cross section: 2.2 fb**

Source of uncertainty	EWK [%]	Total (EWK+QCD) [%] SR	CR
Statistical	40	9	4
Jet energy scale	36	9	4
Theory	10	5	4
All other	8	5	6
Total systematic	38	11	8

Dominated by jet energy scale unc.

VBS Zγ + 2j: aQGC

- New physics could induce charged (WWZγ) and neutral (ZZZγ, ZZγγ, Zγγγ; avoided in SM) aQGCs
  - contribution expected to increase with photon E_T
- Neutrino and charged lepton channel used in aQGC region
- **Parametrisation**: parity conserving EFT Lagrangian with higher dim operators
- Form factor (FF) introduced to restore unitarity at very high energy √s

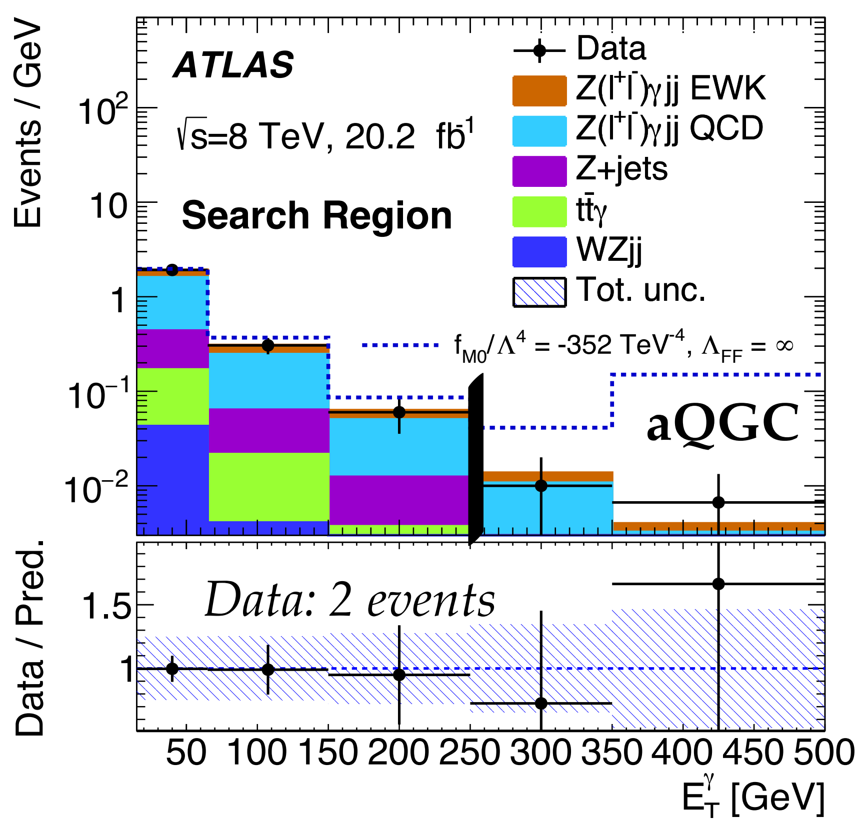
$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

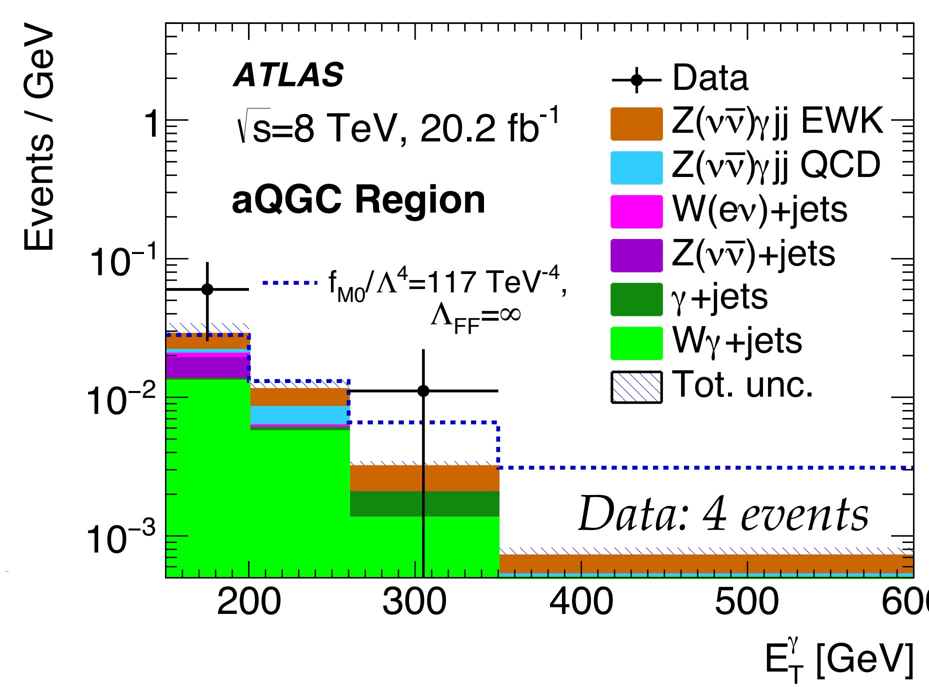
Dim 8 operators

New physics scale

aQGC ννγ selection:
- E_{Tmiss} > 100 GeV, 1γ p_T>150 GeV
- 2 jets with p_T>30 GeV,
- lepton veto (reduce Wγjj bkg), angular cuts (remove γ +jet bkg)
- centrality < 0.3 ; p_T balance < 0.1 ; m_{jj}> 600 GeV (to reduce QCD)
- N_{exp} = 0.65 +/- 0.05

	WWZγ	ZZZγ	ZZγγ	Zγγγ
FM_{0-7}	✓	✓	✓	
FT_{0-7}	✓	✓	✓	✓
FT_{8-9}		✓	✓	✓





Bkg in νν channel :
Wγ+jets (59%) norm. from data with 41% syst.
Z+jets (15%) 2D sideband method with 50% syst.

VBS Zγ + 2j: aQGC results

- **Upper limit on cross section (log-likelihood fit, CLs technique)** :
  - **1.06fb** (0.99 exp.) ννγ and **1.03fb** (1.01fb exp.) $\ell\ell$-γ
- aQGC XS computed with VBFNLO, Madgraph used to study selection efficiency
- One dim. profile likelihood fit -> 95%CL intervals
- Best expected interval: ννγ, **improved by 10-30% when including $\ell\ell$-γ**
- Uncertainties dominated by QCD renormalization and factorization scale (~8%)
- Intervals reduced compared to previous CMS publication

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK *(result without FF to compare with CMS)*	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]
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK arXiv: 1702.03025	f_{T9}/Λ^4	[−4.0, 4.0]	[−6.0, 6.0]
	f_{T8}/Λ^4	[−1.8, 1.8]	[−2.7, 2.7]
	f_{T0}/Λ^4	[−3.8, 3.4]	[−5.1, 5.1]
	f_{M0}/Λ^4	[−71, 75]	[−109, 111]
	f_{M1}/Λ^4	[−190, 182]	[−281, 280]
	f_{M2}/Λ^4	[−32, 31]	[−47, 47]
	f_{M3}/Λ^4	[−58, 59]	[−87, 87]

Summary

- **New important results on VBF/VBS topologies with 7 and 8 TeV data.**

- VBF W:
  - 8 TeV: most precise measurement on VBF topology to this date
  - First observation with >5σ of VBF W channel
  - EWK fiducial XS already systematically dominated and has sensitivity to constraint MC modelling
  - Many differential measurements provided, comparison with 3 generators. Lot of useful information to help improving MC modelling (HEPDATA)
  - First constraints on CP-violating aTGCs parameters

- VBS Zg :
  - Best limits on FT8 and FT9 operators in EFT parametrisation of aQGC
  - Measurement of total and EWK Zγjj cross section in special fiducial regions
  - Very small cross section, need more data for an observation

- **In VBF/VBS processes, JES is generally one of the limiting uncertainties !**

- More results to come with 13 TeV data and larger data sample
  - Possibility to observe for the first time rare VBS processes and put more stringent limits on aTGCs and aQGCs
  - Will allow to check the dependence of XS with $\sqrt{s}$ for a given process

- **Stay tuned !**

Conclusions

	Observed ?	Measurements	
VBF Z @ 8 TeV *JHEP 04(2014)031*	**Yes, >5σ**	Inclusive and EW fiducial XS, differential XS (Powheg, Sherpa 1.4.3), aTGCs	
VBS ssW @ 8 TeV *PRL 113, 141803 (2014), arXiv:1611.02428*	**No, 4.5σ**	EW fiducial XS, aQGCs	
VBS WZ @ 8 TeV *PRD 93, 092004 (2016)*	**No, <2σ**	Upper limit EW XS, aQGCs	
VBF W *arXiv:1703.04362*	**Yes, >5σ**	Inclusive and EW fiducial XS, differential XS (Powheg, Sherpa 1.4.3), aTGCs	NEW !
VBS Zγ *arXiv:1705.01966*	**No, 2σ**	Inclusive and EW XS, aQGCs	NEW !

Extra material

VBF W: MC samples

Process	MC generator	$\sigma \cdot \mathcal{B}$ [pb] 7 TeV	8 TeV
$W(\to e\nu, \mu\nu)$ + 2 jets			
2 EW vertices	Powheg + Pythia8	4670	5340
4 EW vertices (no dibosons)	Powheg + Pythia8	2.7	3.4
$W(\to \tau\nu)$ inclusive			
2 EW vertices	Sherpa	10100	11900
$W(\to \tau\nu)$ + 2 jets			
4 EW vertices (with dibosons)	Sherpa	8.4	
4 EW vertices (no dibosons)	Sherpa		4.2
Top quarks			
$t\bar{t}(\to \ell\nu b\bar{q}q\bar{b}, \ell\nu b\ell\nu\bar{b})$	mc@nlo + Herwig	90.0	
	Powheg + Pythia6		114
tW	AcerMC + Pythia6	15.3	
	mc@nlo + Herwig		20.7
$t\bar{b}q \to \ell\nu b\bar{b}q$	AcerMC + Pythia6	23.5	25.8
$t\bar{b} \to \ell\nu b\bar{b}$	AcerMC + Pythia6	1.0	
	mc@nlo + Herwig		1.7
$Z(\to \ell\ell)$ inclusive, $m_{\ell\ell} > 40$ GeV			
2 EW vertices	Sherpa	3140	3620
$Z(\to ee, \mu\mu)$ + 2 jets, $m_{ee,\mu\mu} > 40$ GeV			
4 EW vertices (no dibosons)	Sherpa	0.7	0.9
Dibosons			
WW	Herwig++	45.9	56.8
WZ	Herwig++	18.4	22.5
ZZ	Herwig++	6.0	7.2

VBF W: selection, event yield

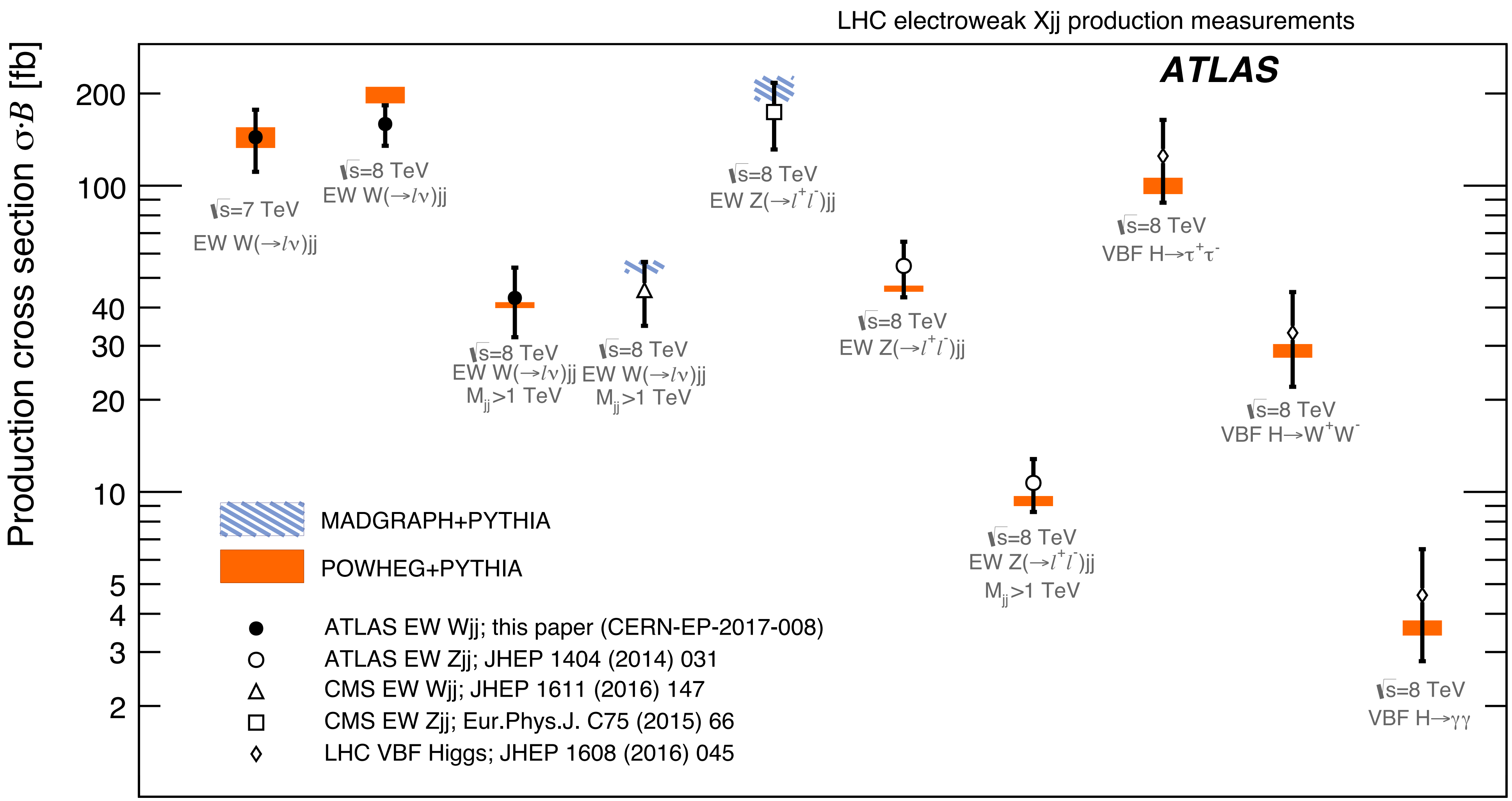
Region name	Requirements
Preselection	Lepton $p_{T} > 25$ GeV
	Lepton $|\eta| < 2.5$
	$E_{T}^{miss} > 20$ GeV
	$m_{T} > 40$ GeV
	$p_{T}^{j_1} > 80$ GeV
	$p_{T}^{j_2} > 60$ GeV
	Jet $|y| < 4.4$
	$M_{jj} > 500$ GeV
	$\Delta y(j_1, j_2) > 2$
	$\Delta R(j, \ell) > 0.3$
Fiducial and differential measurements	
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

Process	7 TeV	8 TeV
Wjj (EW)	920	5600
Wjj (QCD)	3020	19600
Multijets	500	2350
$t\bar{t}$	430	1960
Single top	244	1470
Zjj (QCD)	470	1140
Dibosons	126	272
Zjj (EW)	5	79
Total SM	5700	32500
Data	6063	33719

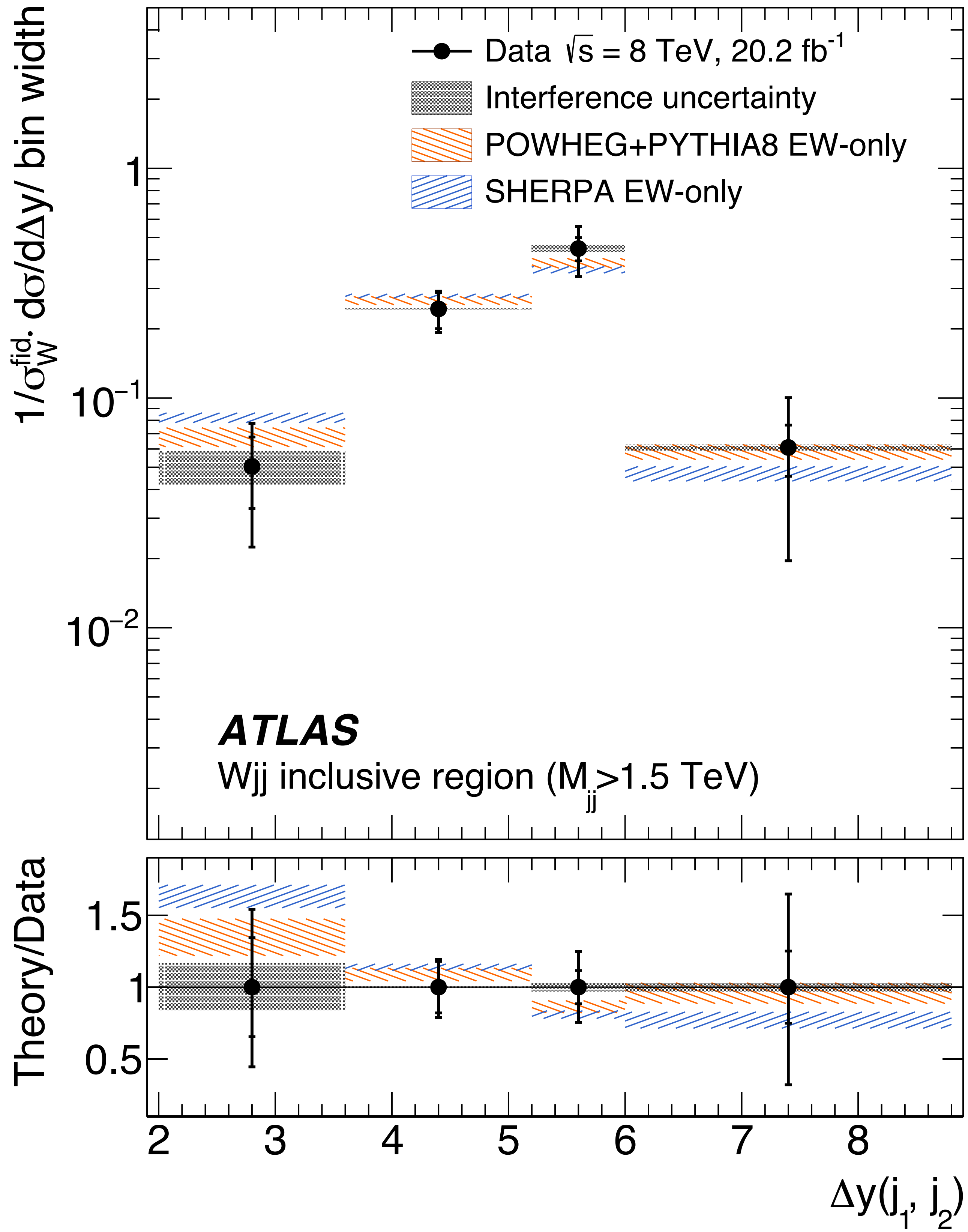
Region name	7 TeV		8 TeV	
	SM prediction	Data	SM prediction	Data
Fiducial and differential measurements				
Signal region	5700	6063	32500	33719
Forward-lepton control region	5000	5273	29400	30986
Central-jet validation region	2170	2187	12400	12677
Differential measurement only				
Inclusive region, $M_{jj} > 500$ GeV	-	-	106000	107040
Inclusive region, $M_{jj} > 1$ TeV	-	-	17400	16849
Inclusive region, $M_{jj} > 1.5$ TeV	-	-	3900	3611
Inclusive region, $M_{jj} > 2$ TeV	-	-	1040	890
Forward-lepton/central-jet region	-	-	12000	12267
High-mass signal region	-	-	6100	6052
Anomalous coupling measurements only				

VBF W: results

Fiducial region	$\sigma^{\text{fid}}_{Wjj} \times \mathcal{B}_{W\to\ell\nu}$ [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



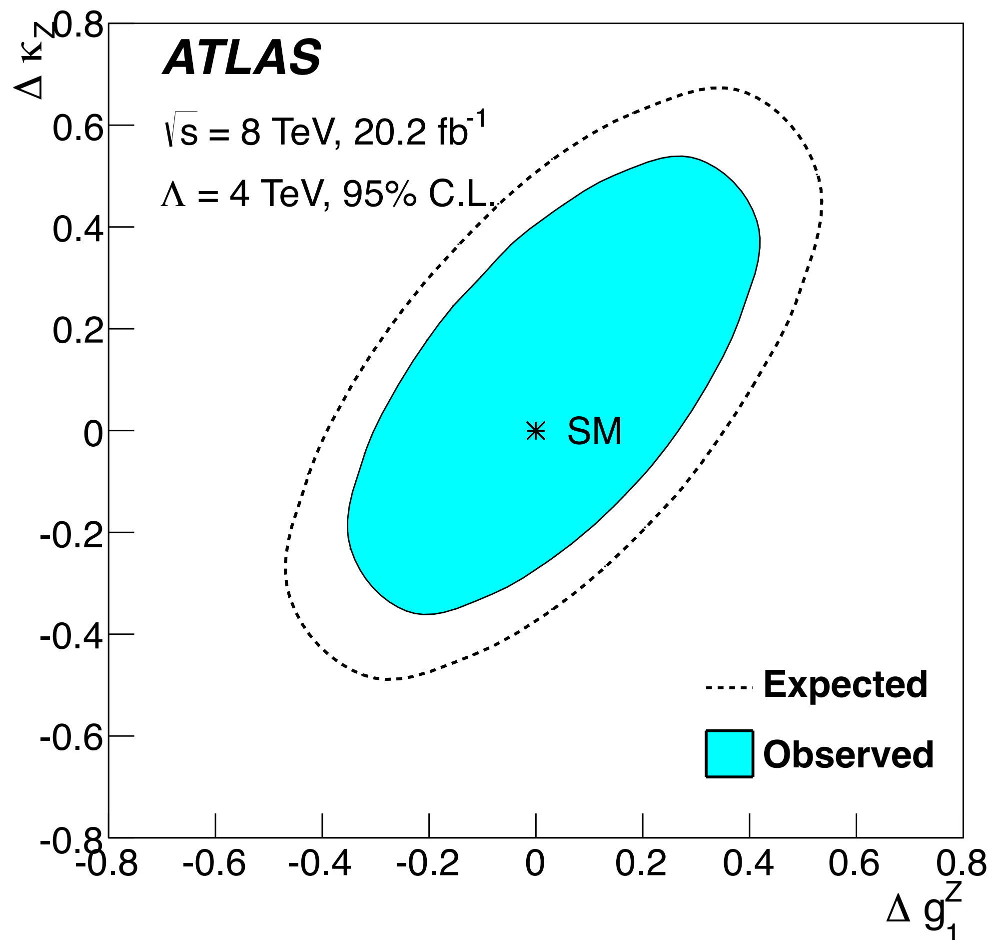
VBF W: signal enhanced region



Interference taken as an uncertainty, that start to be non-negligible in signal enhanced region, and in some specific phase space (small ΔYjj, high jet p_T, …)

VBF W: more details

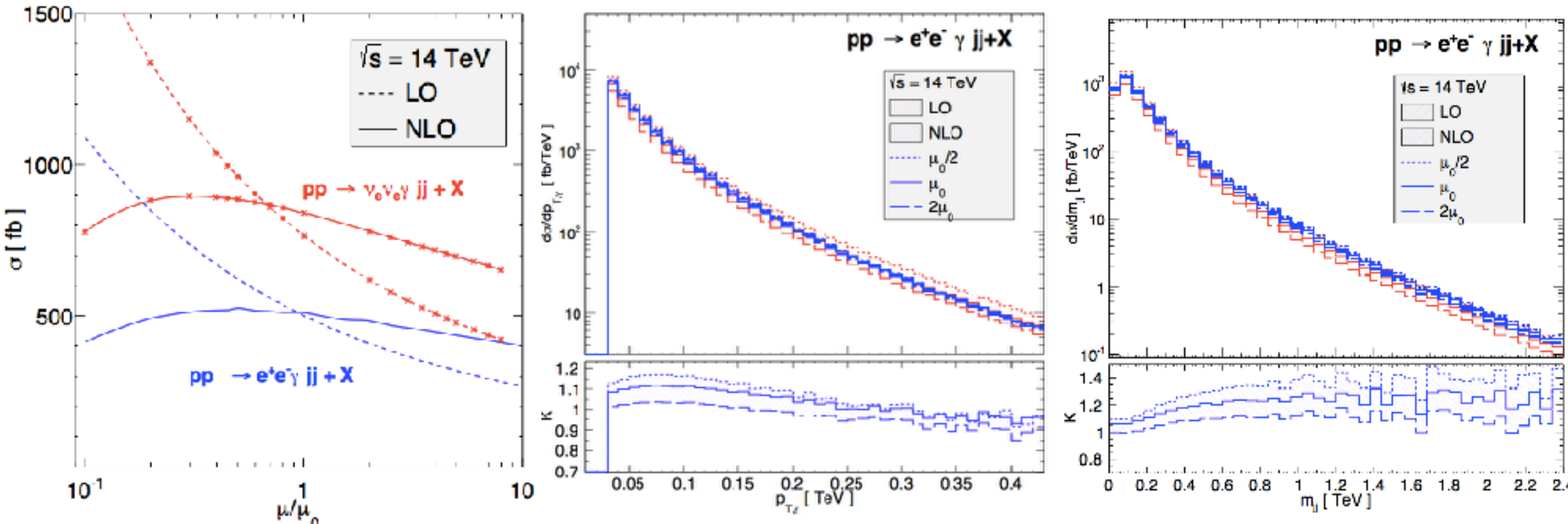
Source	Uncertainty in μ_{EW} 7 TeV	8 TeV
Statistical		
Signal region	0.094	0.028
Control region	0.127	0.044
Experimental		
Jet energy scale (η intercalibration)	0.124	0.053
Jet energy scale and resolution (other)	0.096	0.059
Luminosity	0.018	0.019
Lepton and E_T^{miss} reconstruction	0.021	0.012
Multijet 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



VBFNLO

arXiv:1407.7857

- Scale uncertainty significantly reduced at NLO.
- Size of NLO QCD correction are particularly large in region where VBS is enhanced



VBS Zγ: more details (l+l- channel)

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

	Inclusive region $Z(\ell^+\ell^-)\gamma + \geq 2$ jets		Control region $150 < m_{jj} < 500$ GeV		Search region $m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	781	949	362	421	58	72
Z+jets bkg.	134 ± 36	154 ± 42	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	88 ± 17	91 ± 18	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{\mathrm{data}} - N_{\mathrm{bkg}}$	559 ± 46	704 ± 53	258 ± 24	308 ± 27	44 ± 7	58 ± 8
$N_{Z\gamma\ \mathrm{QCD}}$ (SHERPA MC)	583 ± 41	671 ± 47	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\ \mathrm{EWK}}$ (SHERPA MC)	25.4 ± 1.5	27.3 ± 1.7	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7
$N_{Z\gamma}$ (SHERPA MC)	608 ± 42	698 ± 49	258 ± 25	299 ± 27	48 ± 6	53 ± 6

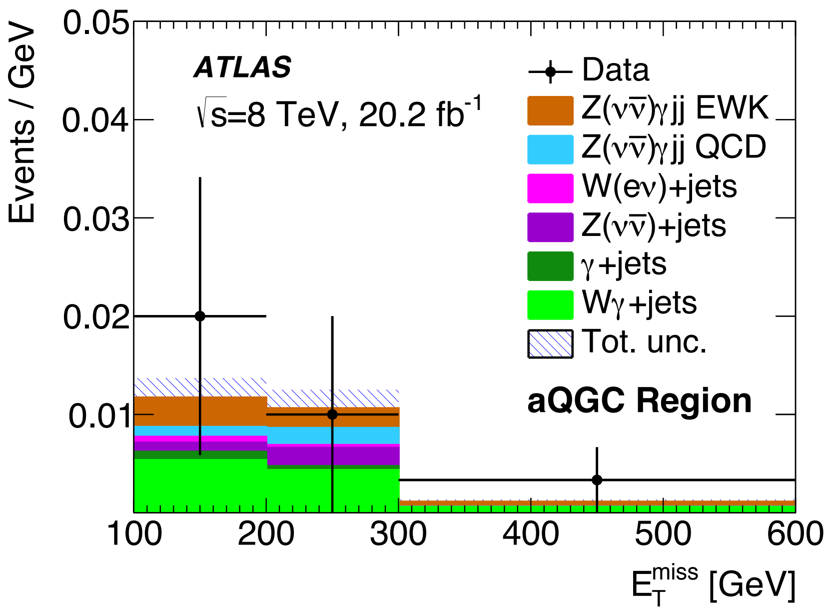
VBS Zγ: more details (νν channel)

Objects	Particle- (Parton-) level selection
Neutrinos	$E_T^{\nu\bar{\nu}} > 100$ GeV
Photon (kinematics)	$E_T^{\gamma} > 150$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.4$
Photon (isolation)	$E_T^{\text{iso}} < 0.5 \cdot E_T^{\gamma}$
Generator-level jets (Outgoing quarks) $(pp \to Z\gamma qq)$	At least two jets (quarks) $E_T^{j(q)} > 30$ GeV, $\lvert\eta^{j(q)}\rvert < 4.5$ $\Delta R(\gamma, j(q)) > 0.4$
Event kinematic selection	$\lvert\Delta\phi(E_T^{\nu\bar{\nu}}, \gamma jj(qq))\rvert > \frac{3\pi}{4}$ $\lvert\Delta\phi(E_T^{\nu\bar{\nu}}, \gamma)\rvert > \frac{\pi}{2}$ $\lvert\Delta\phi(E_T^{\nu\bar{\nu}}, j(q))\rvert > 1$ $E_T^{\gamma} > 150$ GeV $\lvert\Delta y_{jj(qq)}\rvert > 2.5$ ζ_{γ} ¡ 0.3 $p_T^{\text{balance}} < 0.1$ $m_{jj(qq)} > 600$ GeV

	aQGC region	
	$m_{jj} > 500$ GeV $E_T^{\gamma} > 250$ GeV $\ell^+\ell^-\gamma jj$	$m_{jj} > 600$ GeV $E_T^{\gamma} > 150$ GeV $\nu\bar{\nu}\gamma jj$
Data	2	4
Z+jets background	0.28 ± 0.08	0.3 ± 0.2
$W(\ell\nu)\gamma$+jets background	-	1.1 ± 0.5
γ+jets background	-	0.13 ± 0.08
$W(e\nu)$+jets background	-	0.09 ± 0.04
$t\bar{t}\gamma$, WZ background	0.02 ± 0.01	-
$N_{\text{data}} - N_{\text{bkg}}$	1.7 ± 1.4	2.4 ± 2.0
$N_{Z\gamma\ \text{QCD}}$ (SHERPA MC)	1.2 ± 0.4	0.29 ± 0.07
$N_{Z\gamma\ \text{EWK}}$ (SHERPA MC)	0.41 ± 0.04	0.65 ± 0.05
$N_{Z\gamma}$ (SHERPA MC)	1.6 ± 0.4	0.9 ± 0.1

VBS Zγ: more details (results)

	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
$n = 0$	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
$n = 2$	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8



Channel	Phase-space region	Process type	Measured cross-section [fb]	Predicted cross-section [fb]
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK	1.1 ± 0.5 (stat) ± 0.4 (syst)	0.94 ± 0.09
$Z(\ell^+\ell^-)\gamma jj$	Search region	EWK+QCD	3.4 ± 0.3 (stat) ± 0.4 (syst)	4.0 ± 0.4
$Z(\ell^+\ell^-)\gamma jj$	Control region	EWK+QCD	21.9 ± 0.9 (stat) ± 1.8 (syst)	22.9 ± 1.9