VBF – V from ATLAS

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on behalf of the EW W, Z analysis teams
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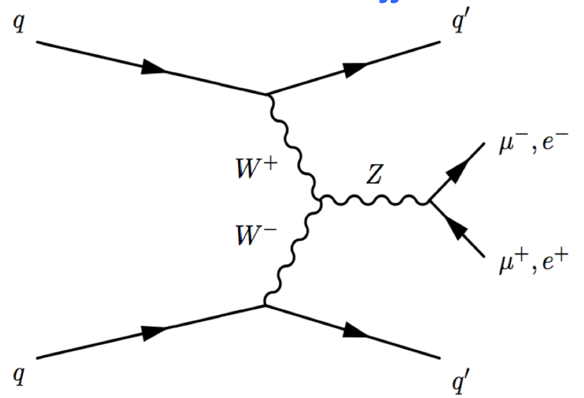
LHC-EWWG

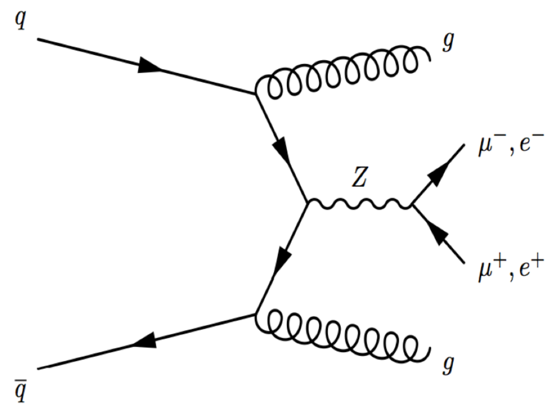
ATLAS Collaboration, JHEP 04 (2014) 031 and PLB 775 (2017) 206

Measurement of VBF Zjj production at √s=8TeV and √s=13TeV

Electroweak Zjj



Strong Zjj



- EWK Zjj production is *rare*, just 1% of the inclusive Zjj production at the LHC
  - Extract electroweak cross section in EWK-enhanced phase space regions (high m_{jj}, low central jet activity)
  - Measure inclusive Zjj cross sections to ensure longevity

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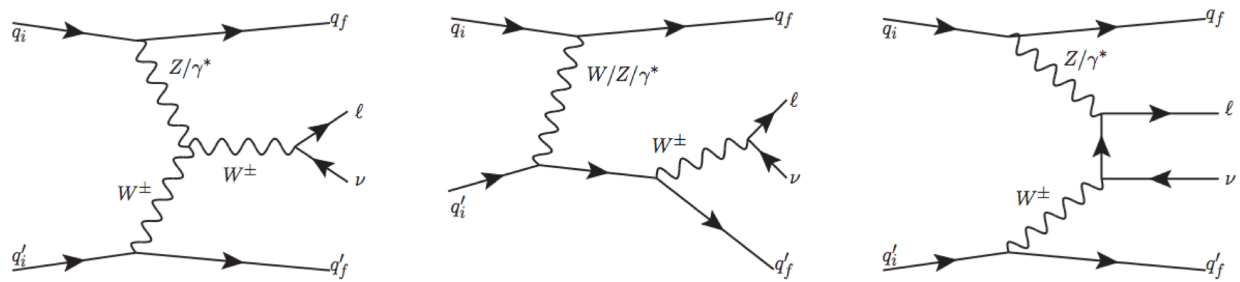
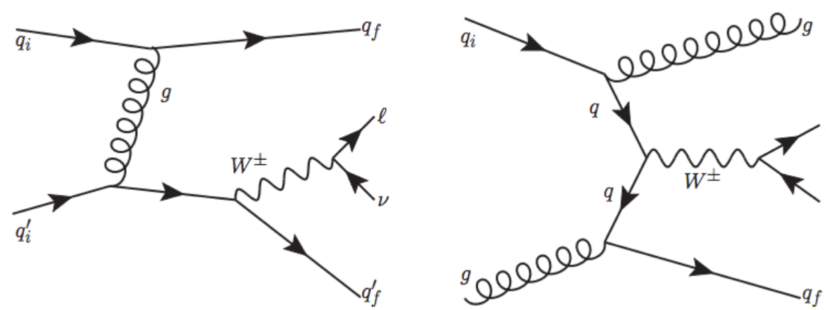
Measurements of VBF Wjj production at √s=7TeV and √s=8TeV

Electroweak signal processes



(a) Vector boson fusion (b) W bremsstrahlung (c) Non-resonant

Strong background processes



- Fiducial cross section measurement using control region to constrain shape of strong Wjj background (technique adapted from 8 TeV Zjj analysis)
- Comprehensive set of differential cross sections (using MC for strong Wjj)
  - Strong and EW Wjj dominated processes (all other backgrounds subtracted)
  - EW Wjj (all backgrounds, including strong Wjj, subtracted)
- Limits on anomalous WWZ, WWγ TGCs

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Zjj: 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	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance,3}} < 0.15$	—

$p_T > 25$ GeV

--- Z-boson selection
--- Baseline jet selection
--- Probe of high-p_T or high-mass
--- Search/control cuts for electroweak extraction

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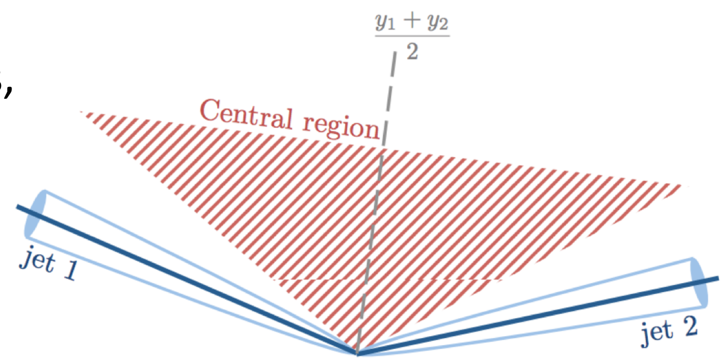
Wjj – several fiducial regions for different measurements

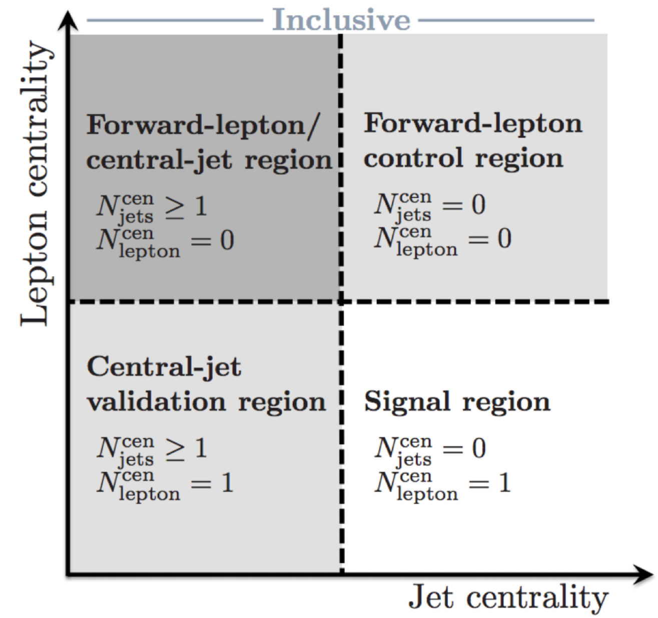
EW Wjj measurement is systematics dominated
-> tighter cuts on hadronic system
Ample statistics allows for broad set of measurements, including first differential EW cross sections.

Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV Lepton $\lvert\eta\rvert < 2.5$ $E_T^{miss} > 25$ 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

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

C ≤ 0.4





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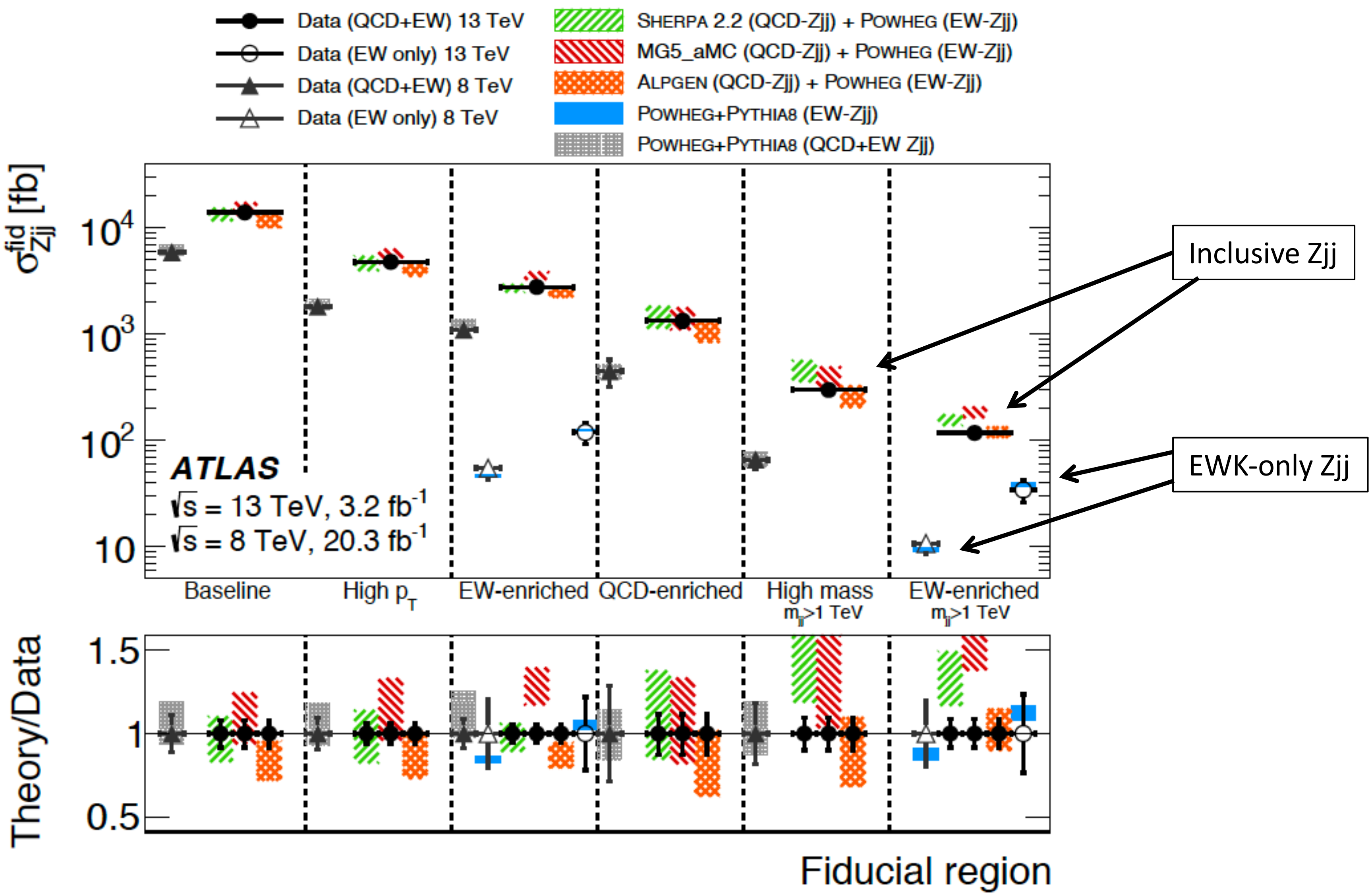
Inclusive Zjj measurements of each region at √s=8TeV and √s=13TeV



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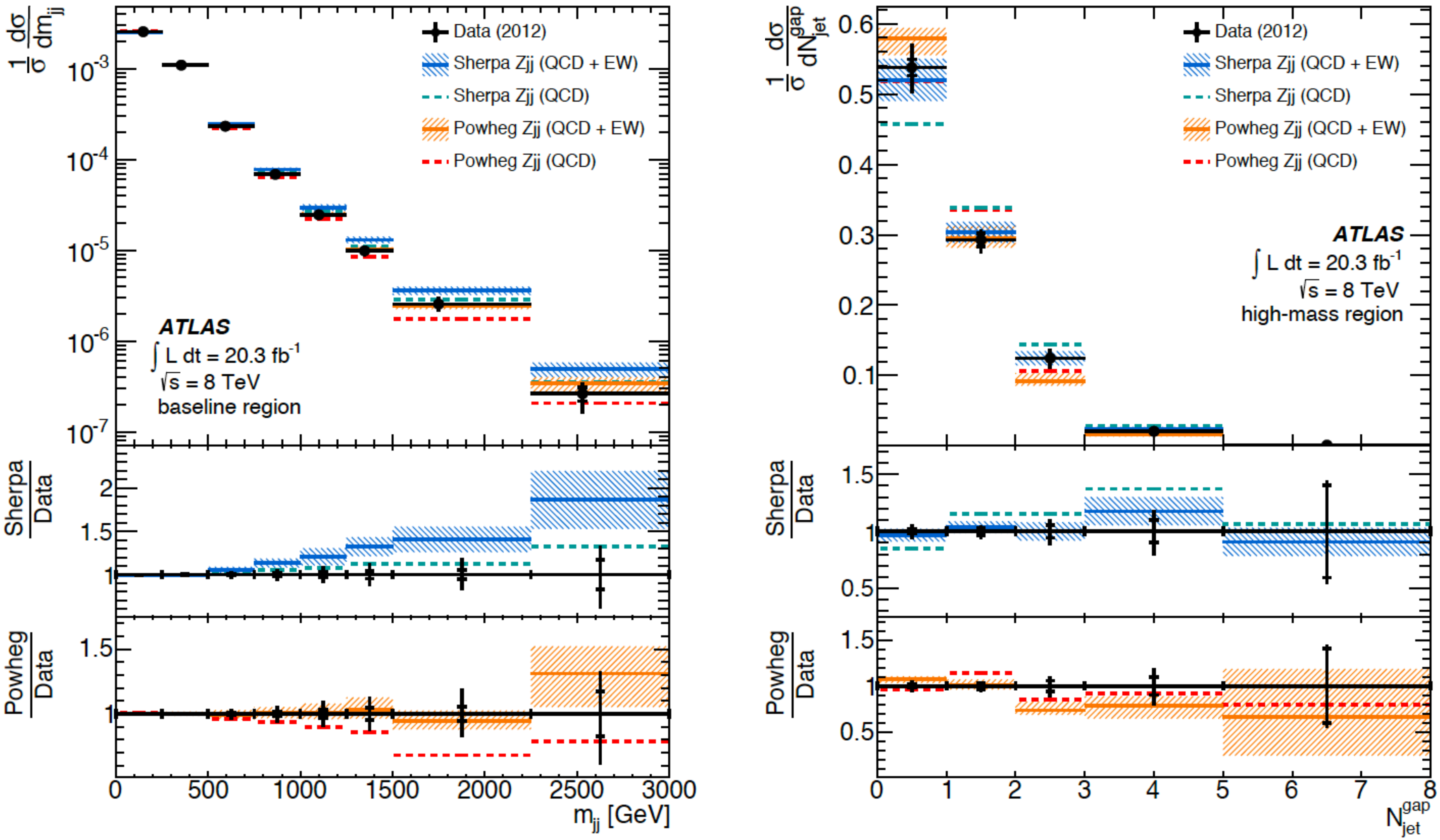
Differential inclusive Zjj cross section measurements



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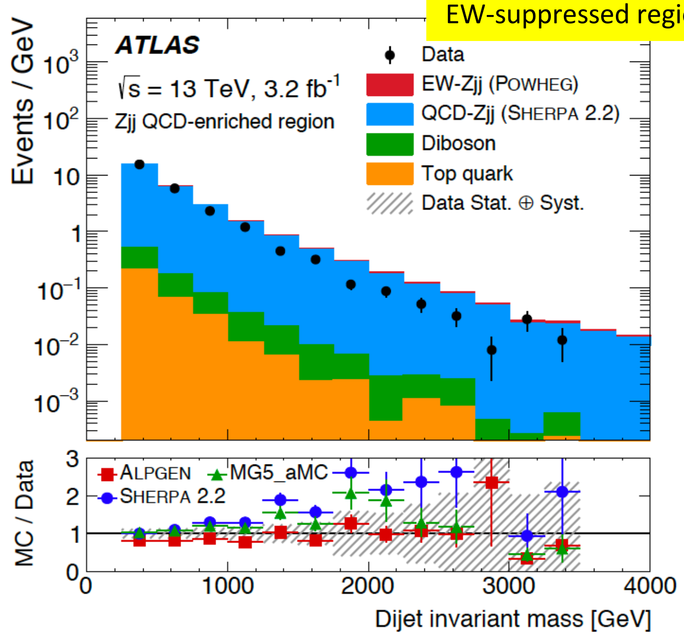
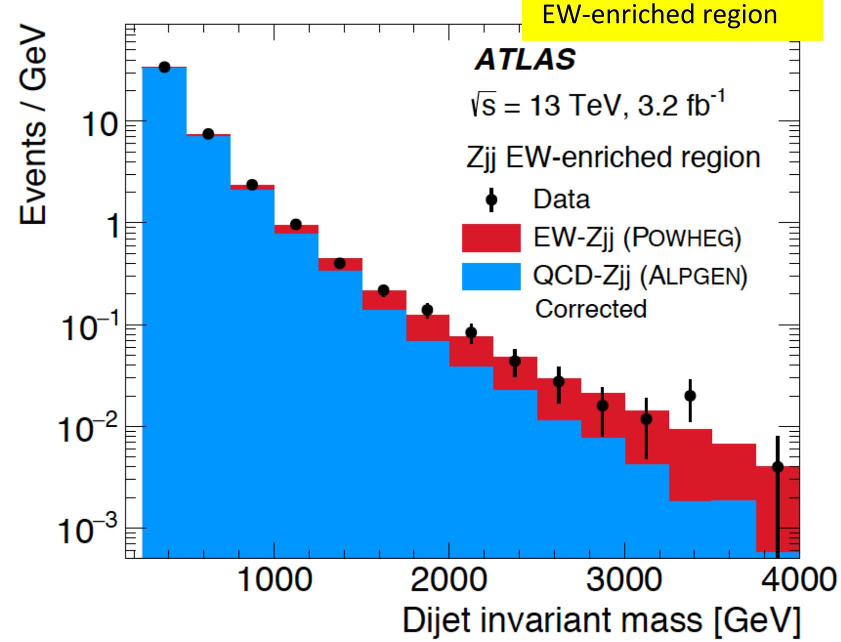
EWK Zjj: extraction of signal

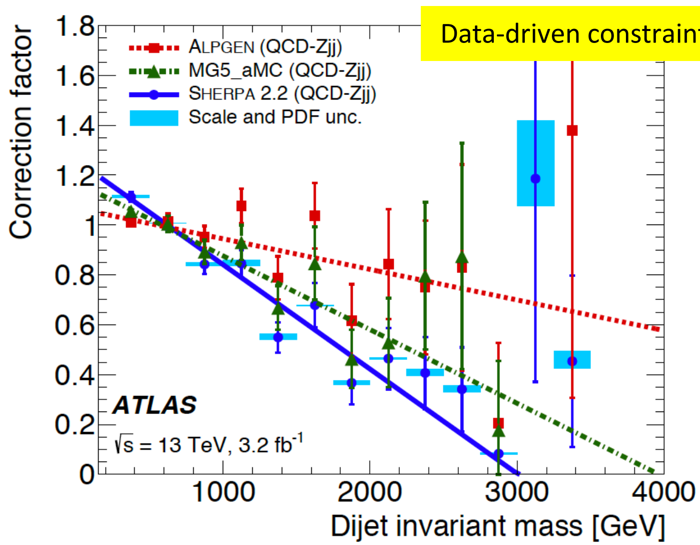
EW-suppressed region



EW-enriched region



Data-driven constraint



- Signal extracted using a two template fit in EWK enhanced *'search'* region
- Strong Zjj background template constrained in a EWK-suppressed *'control'* region
  - Reduces impact of experimental (JES/JER) uncertainties and theoretical modelling uncertainties

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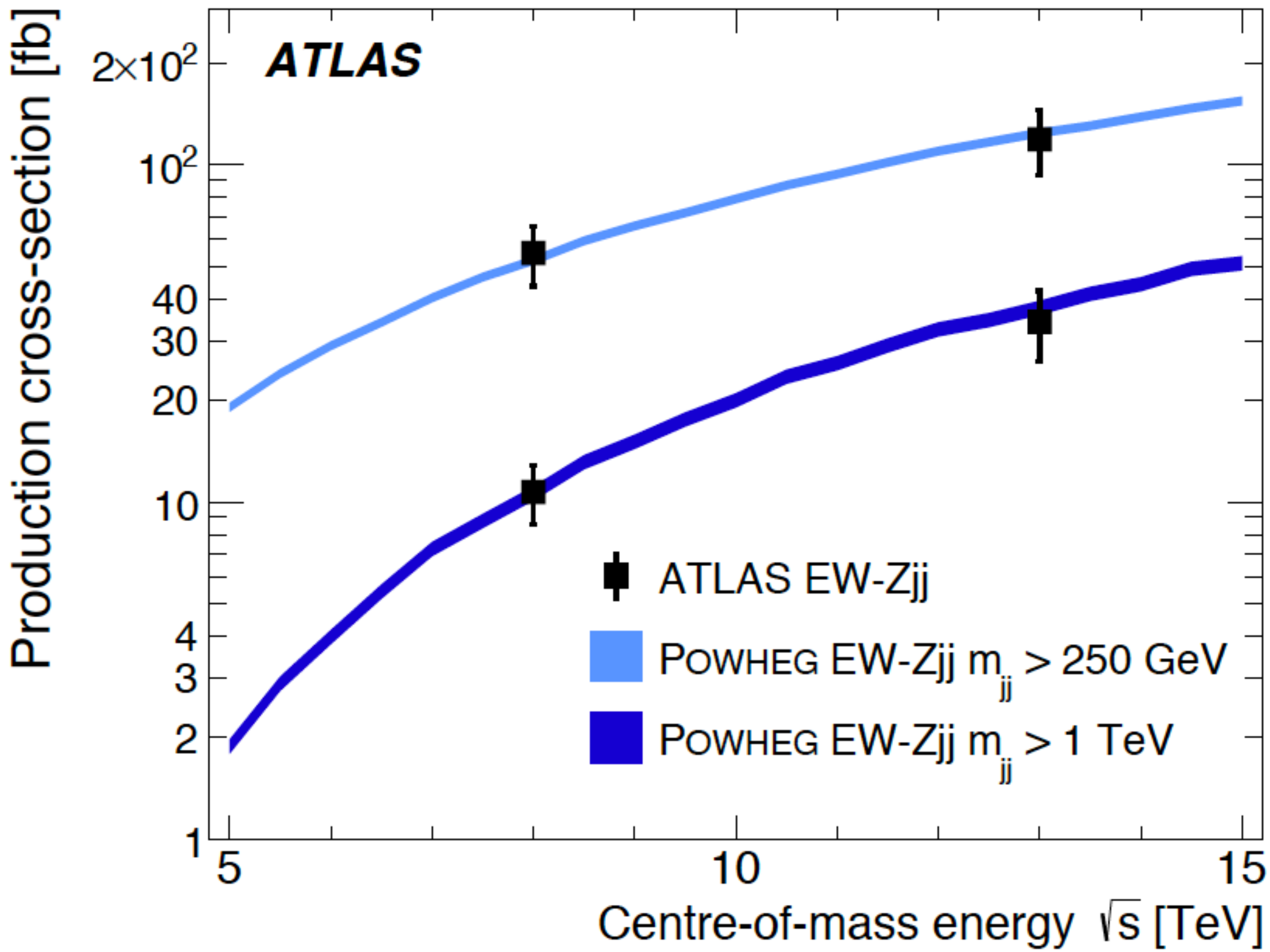
Electroweak Zjj cross sections at √s=8TeV and √s=13TeV



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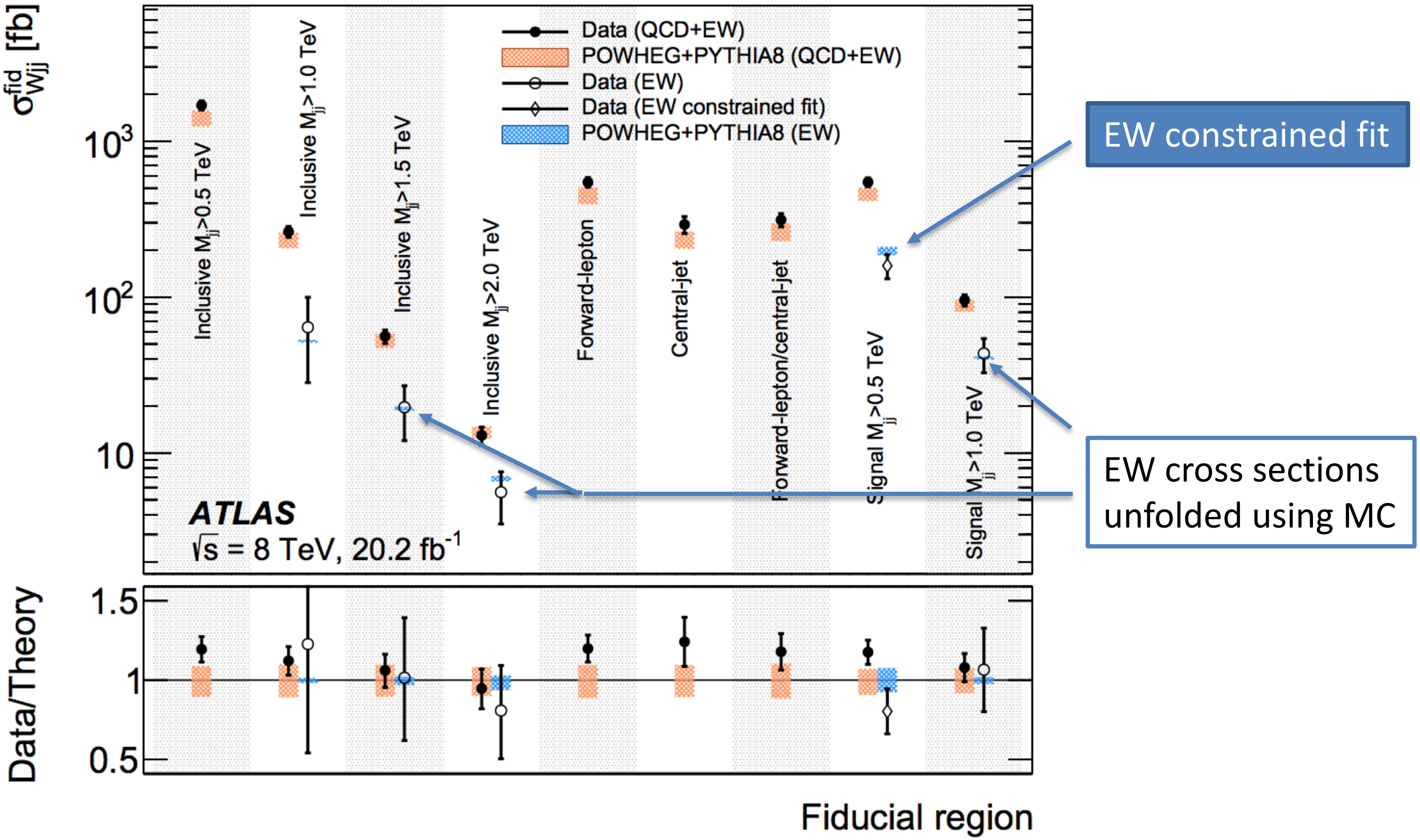
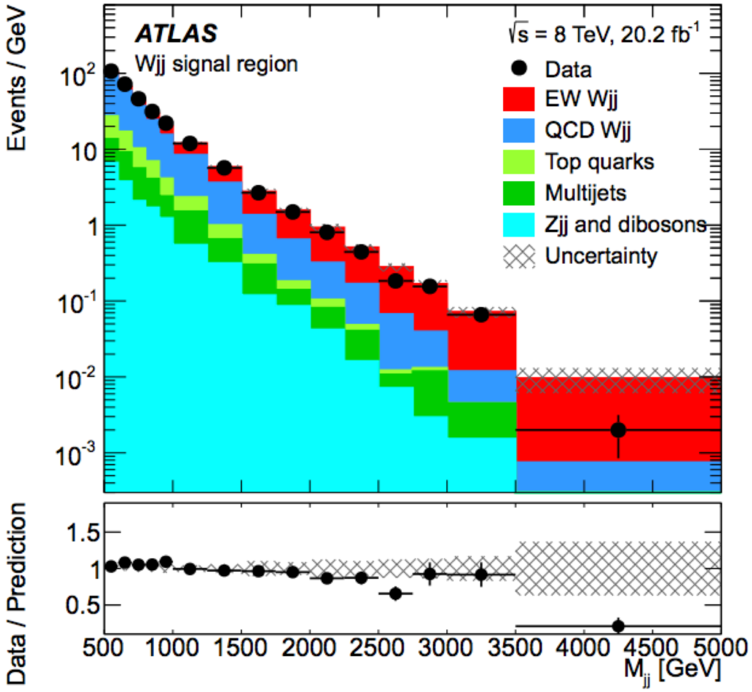
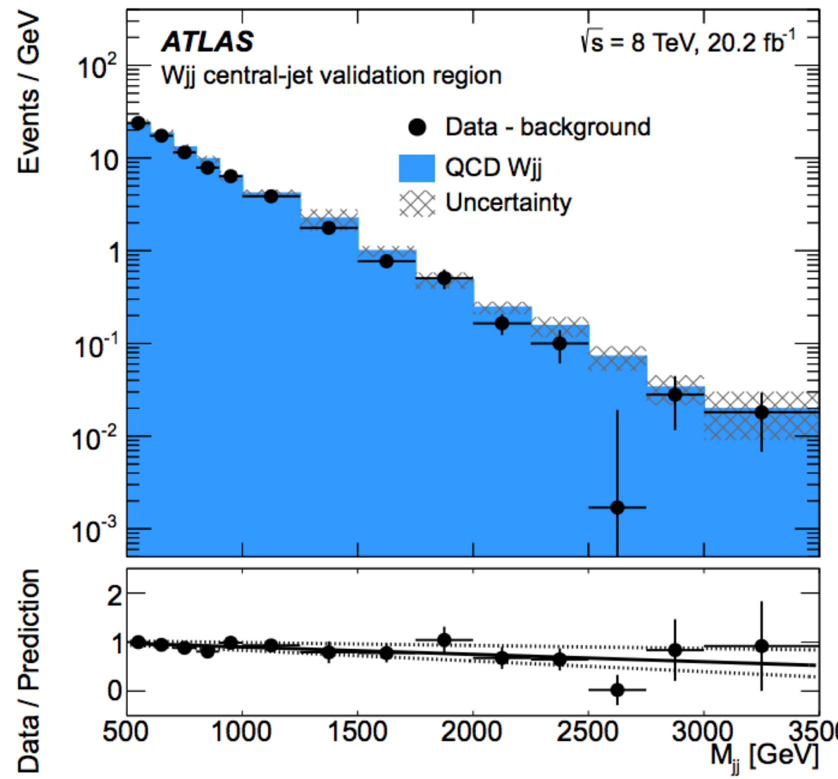
Wjj: inclusive measurements



Wjj: fiducial measurements



- EW Wjj enhanced at high dijet inv. mass
- Data driven Multijets background estimation
- Other backgrounds estimated with MC



- Strong Wjj background constrained with data in control/validation region
- Template fit of dijet mass distribution in signal region used to extract EW cross section
- Uncertainties estimated by propogating 1σ variation through constraint and template fit.

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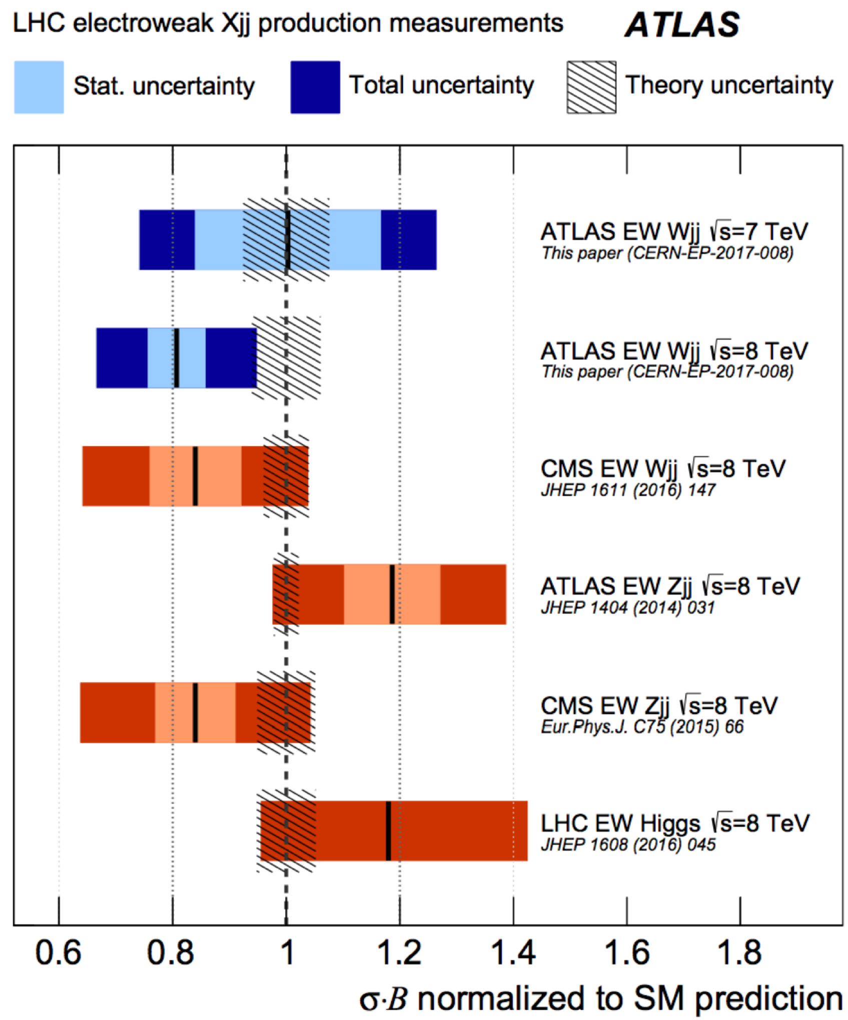
Wjj: fiducial measurements

$\sqrt{s}$	$\sigma^{\text{fid}}_{\text{meas}}$ [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) ± 15 (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



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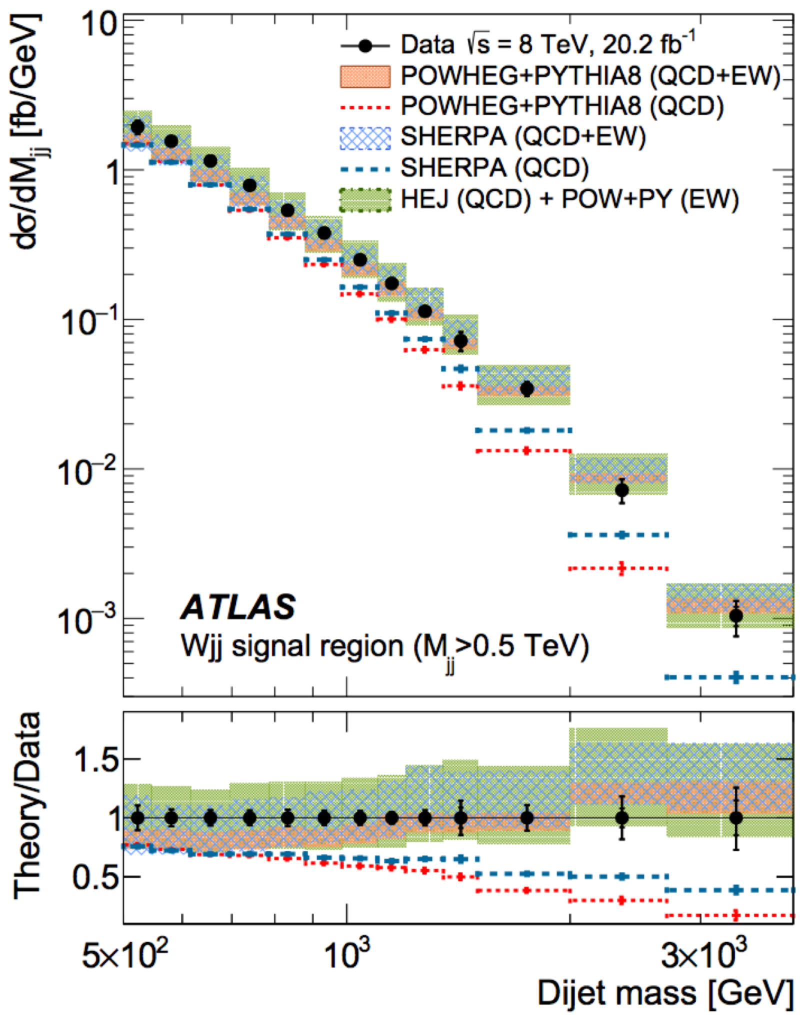
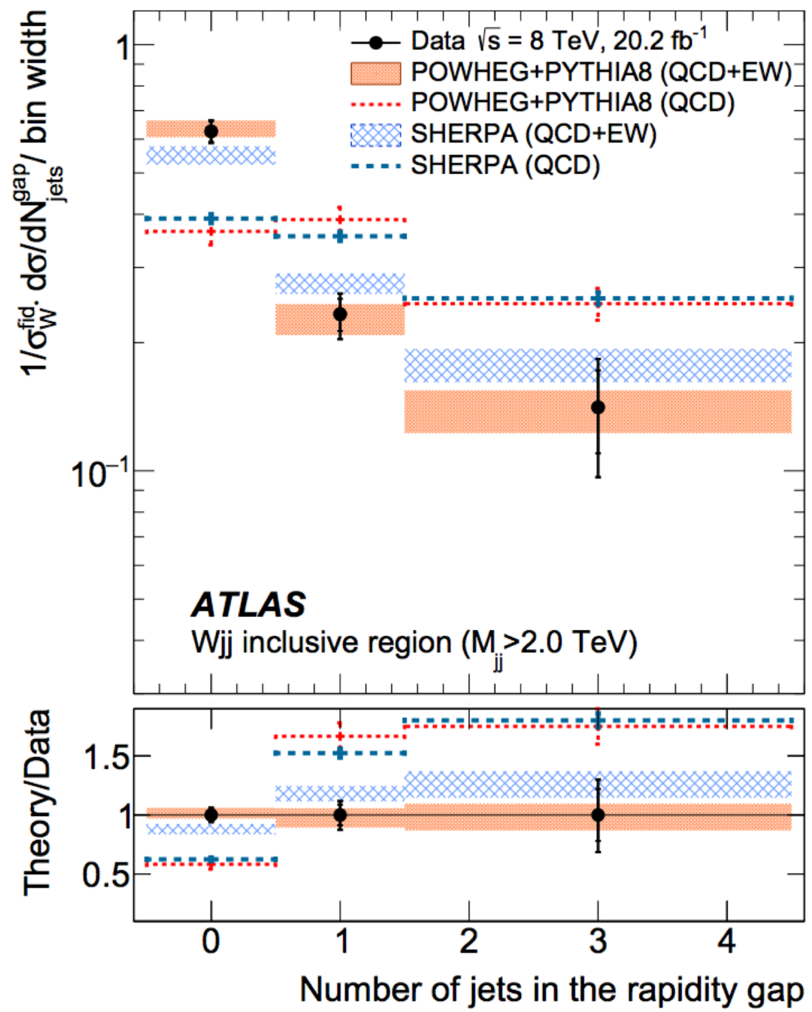
Wjj: differential measurements of Strong+EW Wjj





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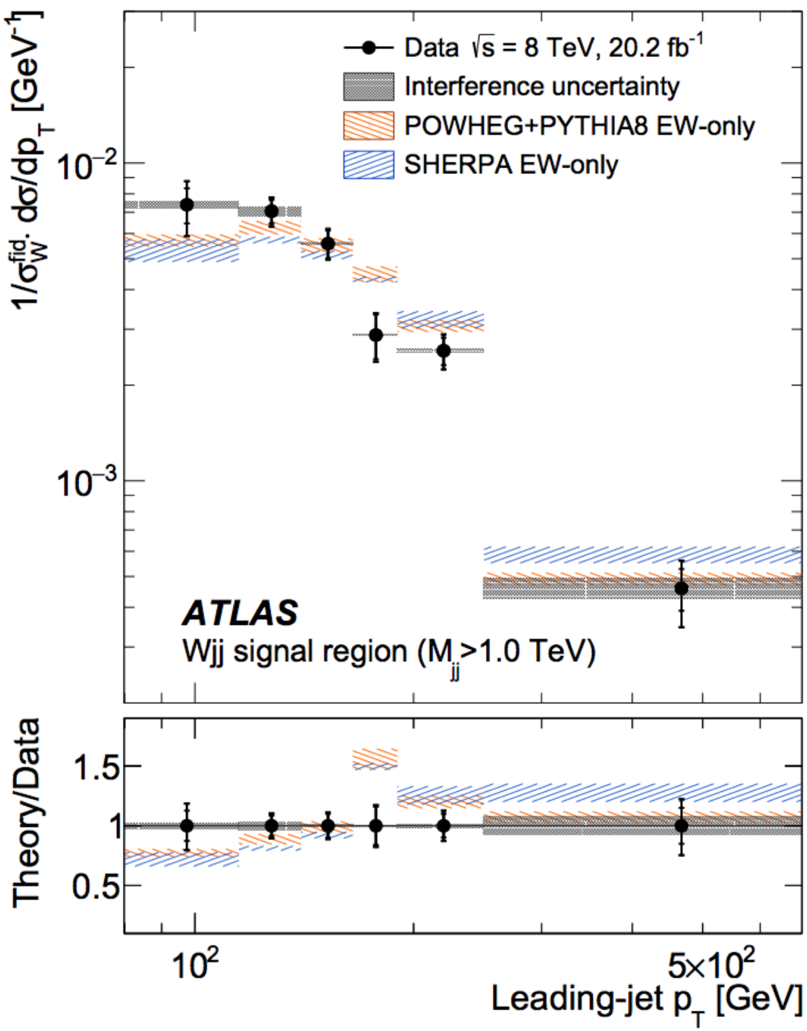
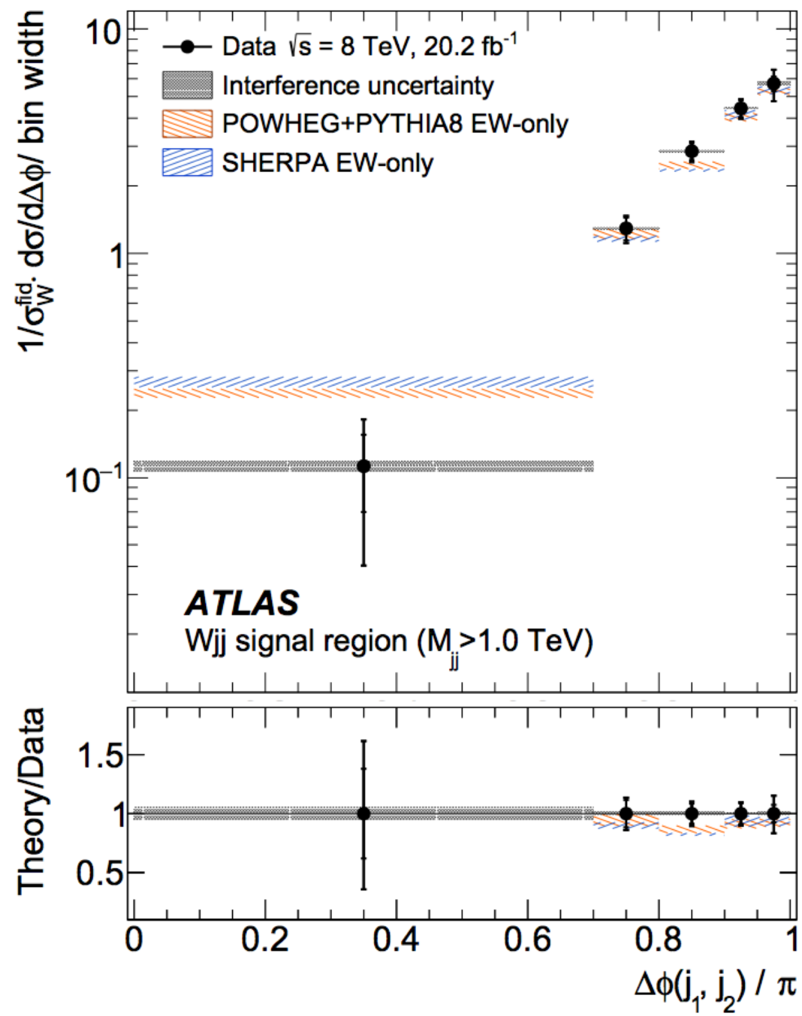
Wjj: differential measurements of EW-only Wjj





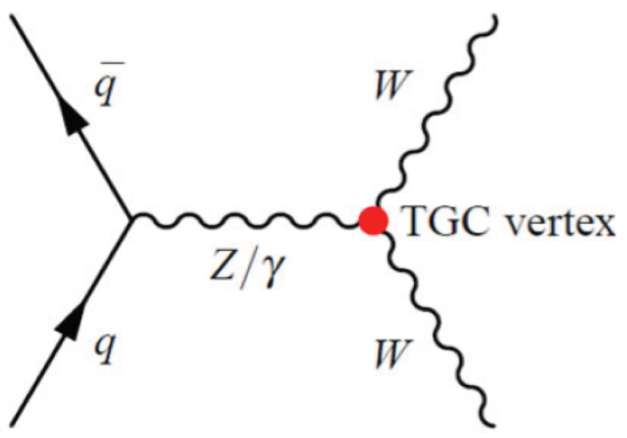
Limits on aTGCs (I)

- Anomalous WWZ couplings parameterised using an effective lagrangian:

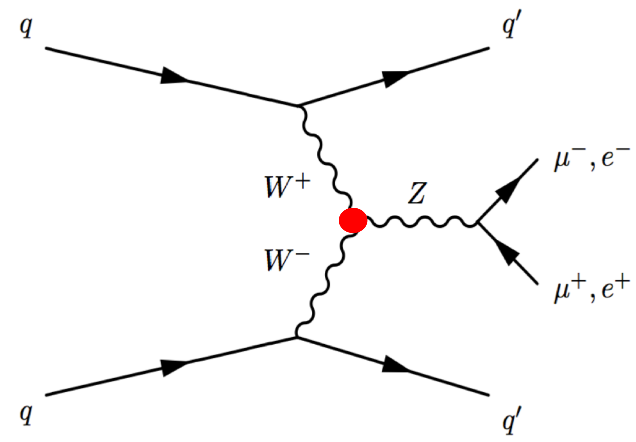
$$i\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV}\Big\{\Big[g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^-\Big]$$

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

Diboson: WW



Electroweak Zjj



On-shell W's, off-shell Z
All bosons timelike, $Q^2>0$

Off-shell W's, on-shell Z
Z-boson timelike, $Q^2>0$
W-bosons space-like, $Q^2<0$

Limits on aTGCs (II) – using Zjj at √s=8TeV

- Number of observed events in data at m_{jj} > 1 TeV used to set limits on the aTGC parameters:
  - SHERPA used to parameterise the m_{jj} dependence on the aTGC.
  - Dipole form factor with two choices of unitarisation scale, Λ=6TeV and Λ=infinity
  - Electroweak cross section also measured in this region, for good measure:

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

$$\sigma_{\rm EW}^{m_{jj}>1\rm TeV} = 10.7 \pm 0.9\,(\rm stat) \pm 1.9\,(\rm syst) \pm 0.3\,(\rm lumi)$$

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Limits on aTGCs (III) – using Wjj at √s=8TeV

- Number of observed events in data at m_{jj} > 1 TeV and $p_{T,jet}$ > 600 GeV used to set limits on the aTGC parameters:
  - SHERPA used to parameterise the m_{jj} dependence on the aTGC.
  - Dipole form factor with two choices of unitarisation scale, Λ=4TeV and Λ=infinity

	$\Lambda = 4$ TeV		$\Lambda = \infty$	
	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	$[-0.16, 0.12]$	$[-0.13, 0.090]$	$[-0.064, 0.054]$	$[-0.053, 0.042]$
$\tilde{\kappa}_Z$	$[-1.7, 1.8]$	$[-1.4, 1.4]$	$[-0.70, 0.70]$	$[-0.56, 0.56]$
$\tilde{\lambda}_V$	$[-0.13, 0.15]$	$[-0.10, 0.12]$	$[-0.058, 0.057]$	$[-0.047, 0.046]$