MEASUREMENTS OF VECTOR BOSON FUSION

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On behalf of the ATLAS Collaboration

Deep Inelastic Scattering and Related Subjects

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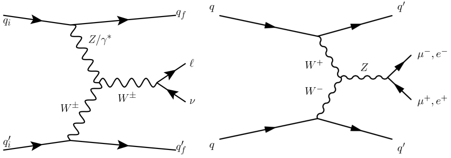
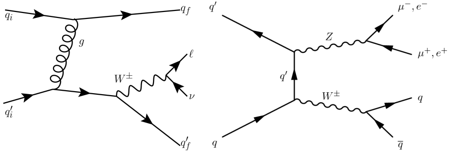
Introduction

- Measurement: electroweak (EW) production of Wjj and Zjj via t-channel exchange of EW boson, including Vector Boson Fusion (VBF)
- Wjj and Zjj final states dominated by processes involving strong interations
- EW-Wjj and Zjj productions measured in signal-enriched fiducial regions. Differential cross sections further unfolded for various observables distinguishing EW and QCD processes.
- VBF process is of particular interest:
  - Measure couplings to Higgs boson
  - Searches for new particles beyond Standard Model (SM)
  - Sensitive to anomalous triple-gauge-boson couplings (WWZ and $WW\gamma$)
  - Tune Monte Carlo simulation

LO Vjj EW-production (VBF):



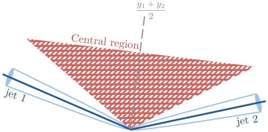
Examples of LO Vjj QCD-production:

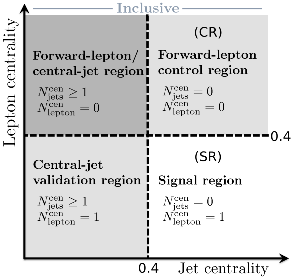


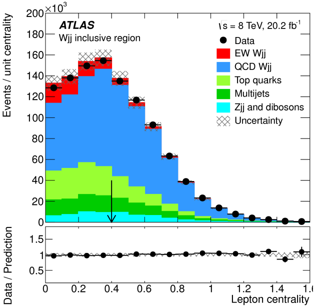
Measurement of electroweak Wjj production – Regions of interest

- Published:
  EPJC 77 (2017) 474 [$\sqrt{s} = 8(7)\,\mathrm{TeV},\ 20.2(4.7)\,\mathrm{fb}^{-1}$]
- e and μ channels combined
- Event pre-selection:
  - High-p_T lead jets: $p_T^{j_1} > 80\,\mathrm{GeV}$, $p_T^{j_2} > 60\,\mathrm{GeV}$
  - Well separated leading jets: $\Delta y(j_1, j_2) > 2$
  - Di-jet invariant mass: $M_{jj} > 500\,\mathrm{GeV}$
  - W boson selection cuts
- Main backgrounds (% of SR in $8\,\mathrm{TeV}$ analysis):
  - QCD-Wjj ($\sim 60\%$)
  - Multijet and top ($\sim 10\%$ each)
- Lepton (jet) centrality:

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

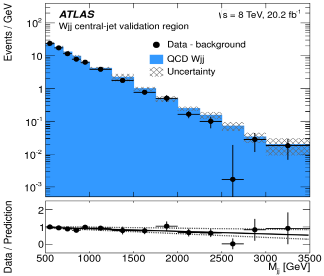


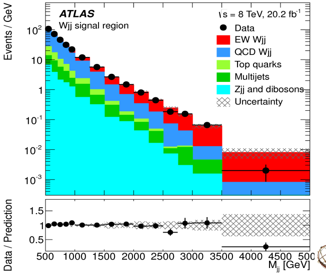




Measurement of electroweak Wjj production – Main background estimates

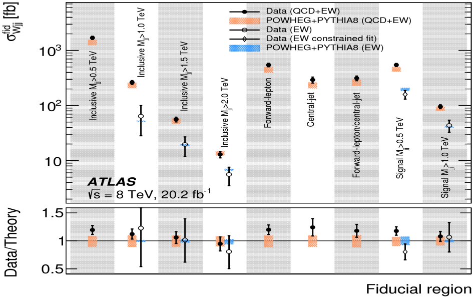
- QCD-Wjj samples simulated by `POWHEG+PYTHIA8`
- Multijet background (in CR and SR) determined by simultaneous fit of multijet-enriched template and QCD-Wjj to data
- Control region constrained QCD-Wjj:
  - QCD-Wjj M_{jj} distribution weighted in SR by fit function determined by ratio of background subtracted data over QCD-Wjj in CR
  - Allows to suppress systematic uncertainties via ratio of simulated SR/CR QCD-Wjj
  - The computed fit function is confirmed in the central-jet validation region
- Final normalizations in SR of (CR-corrected) QCD-Wjj and simulated (`POWHEG+PYTHIA8`) EW-Wjj obtained by global M_{jj} fit to data

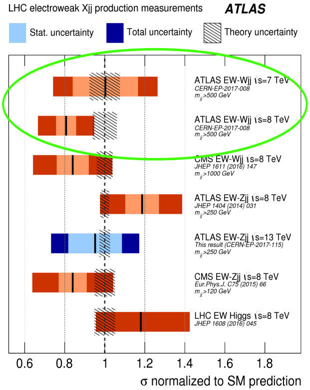




Measurement of electroweak Wjj production – Fiducial cross sections

- σ^{fid}_{Wjj} (fb) measurements in SR (background-only hypothesis rejected at $> 5\sigma$):
  - $7\,\mathrm{TeV}$: $144 \pm 23\,(stat) \pm 23\,(exp) \pm 13\,(th)$ [POWHEG+PYTHIA: 144 ± 11]
  - $8\,\mathrm{TeV}$: $159 \pm 10\,(stat) \pm 17\,(exp) \pm 15\,(th)$ [POWHEG+PYTHIA: 198 ± 12]

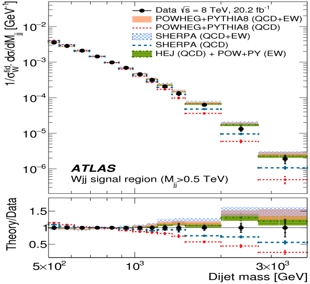


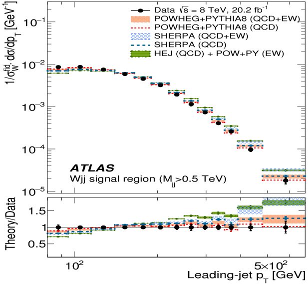


- Systematic uncertainties on σ^{fid}_{Wjj} ($8\,\mathrm{TeV}$):
  - Data statistics in CR: 4.4%
  - Largest experimental: jet calibration ($\sim 8\%$)
  - Largest theoretical: EW-Wjj σ ($\sim 6\%$) ; PDF ($\sim 5\%$) ; EW/QCD-Wjj interference, MC statistics, and EW-Wjj scale and parton shower ($\sim 3\%$ each)

Measurement of electroweak Wjj production – Unfolded differential σ

- Unfolding performed via bayesian iterative technique, for both EW and QCD+EW Wjj production, and for single lepton flavor
- Done in 4 mutually orthogonal fiducial regions, high-M_{jj} EW-enhanced and inclusive regions
- Achieved for observables distinguishing EW/QCD Wjj productions (M_{jj}, $\Delta y(j_1, j_2)$, $C_{l(j)}$, number of additional central jets) and sensitive to anomalous gauge couplings ($\Delta\Phi(j_1, j_2)$, p_T^{j1}, p_T^{jj})
- Comparison to predictions from `POWHEG+PYTHIA8`, `SHERPA` v1.4.3, and `HEJ` (QCD)
- Examples:
  - High-M_{jj} region is better described by `POWHEG+PYTHIA8` and `HEJ`
  - p_T^{j1}, correlated with p transfer in t-channel, better described by `POWHEG+PYTHIA8`



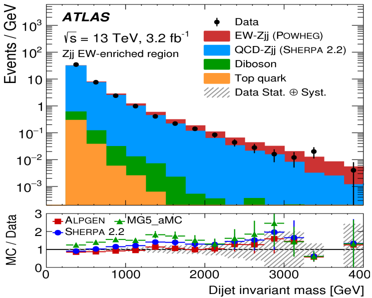


Measurement of electroweak Zjj production – Regions of interest

- Published:
  JHEP 04 (2014) 031 [$\sqrt{s} = 8\,\mathrm{TeV},\ 20.3\,\mathrm{fb}^{-1}$]
  PLB 775 (2017) 206 [$\sqrt{s} = 13\,\mathrm{TeV},\ 3.2\,\mathrm{fb}^{-1}$]
- e and μ channels combined
- Main background: QCD-Zjj
  (95% of $13\,\mathrm{TeV}$ EW-enriched SR)
- $p_T^{balance} = \dfrac{|\overrightarrow{p_T}^{\ell_1} + \overrightarrow{p_T}^{\ell_2} + \overrightarrow{p_T}^{j_1} + \overrightarrow{p_T}^{j_2}|}{|\overrightarrow{p_T}^{\ell_1}| + |\overrightarrow{p_T}^{\ell_2}| + |\overrightarrow{p_T}^{j_1}| + |\overrightarrow{p_T}^{j_2}|}$
  constrained to low values to suppress pileup or multiple parton interactions, and poorly measured jets
- N_{jet}^{gap}: number of jets in the rapidity interval between the two leading jets
- If $N_{jet}^{gap} \geq 1$, $p_T^{balance,3}$ is considered, including highest-p_T-jet in the rapidity gap

Analysis regions:

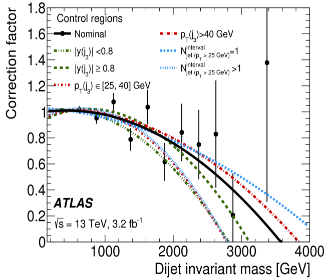
	Fiducial region					
Object	Baseline	High-mass	High-p_{T}	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_{\mathrm{T}} > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_{\mathrm{T}}^{j_1} > 55$ GeV		$p_{\mathrm{T}}^{j_1} > 85$ GeV	$p_{\mathrm{T}}^{j_1} > 55$ GeV		
	$p_{\mathrm{T}}^{j_2} > 45$ GeV		$p_{\mathrm{T}}^{j_2} > 75$ GeV	$p_{\mathrm{T}}^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\mathrm{jet}\ (p_{\mathrm{T}}>25\ \mathrm{GeV})}^{\mathrm{interval}} = 0$		$N_{\mathrm{jet}\ (p_{\mathrm{T}}>25\ \mathrm{GeV})}^{\mathrm{interval}} \geq 1$
Zjj system	—			$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$		$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$

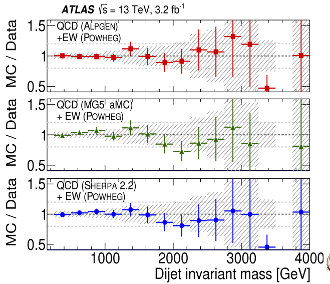


Measurement of electroweak Zjj production – Main Background estimate

- QCD-Zjj template simulated by SHERPA v1.4.3 normalized to NLO ($8\,\mathrm{TeV}$), and the combination of MADGRAPH5_aMC@NLO+PYTHIA8, SHERPA v2.2.1, and ALPGEN+PYTHIA6 ($13\,\mathrm{TeV}$)
- EW-Zjj template simulated by SHERPA v1.4.3 normalized to NLO ($8\,\mathrm{TeV}$), and the combination of POWHEG+PYTHIA8 and SHERPA v2.2.1 ($13\,\mathrm{TeV}$)
- Control region constrained QCD-Zjj:
  - Same method as for Wjj analysis, yet with CR defined by events with ≥ 1 jet in rapidity gap
  - Pairs of mutually exclusive subsets of CR used to bound QCD-Zjj reweighting function
- Simulated signal and (CR-corrected) QCD-Zjj templates scaled to match data via global M_{jj} fit

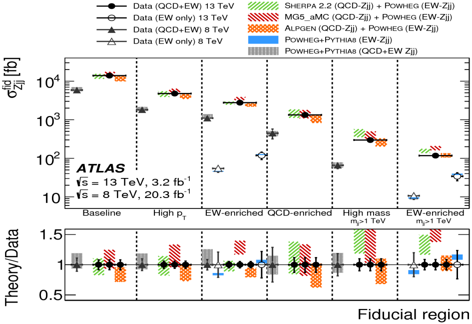
  $13\,\mathrm{TeV}$ case: average of 6 fits derived from all combination of QCD-Zjj and EW-Zjj templates

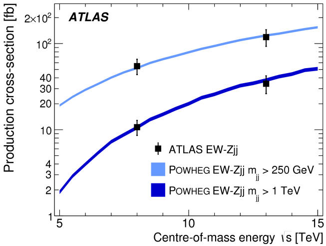




Measurement of electroweak Zjj production – Fiducial cross sections

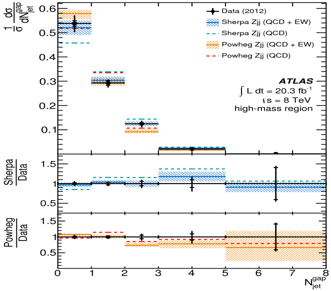
- σ^{fid}_{Zjj} (fb) in $M_{jj} > 250\,\mathrm{GeV}$ region (background-only hypothesis rejected at $> 5\sigma$):
  - $8\,\mathrm{TeV}$: $54.7 \pm 4.6\,(stat)\ ^{+9.8}_{-10.4}\,(syst) \pm 1.5\,(lumi)$ [POWHEG+PYTHIA: 46.1 ± 1.0]
  - $13\,\mathrm{TeV}$: $119 \pm 16\,(stat) \pm 20\,(syst) \pm 2\,(lumi)$ [POWHEG+PYTHIA: 125.2 ± 3.4]
- Systematic uncertainties on σ^{fid}_{Wjj} ($13\,\mathrm{TeV}$, $M_{jj} > 250\,\mathrm{GeV}$ region):
  - Data statistics in CR: 6.2%
  - Largest experimental: jet calibration (5-6%)
  - Largest theoretical: M_{jj} shape (11%) ; QCD-Zjj scale, PDF & showering (4.5%)

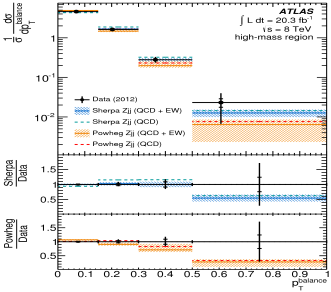




Measurement of electroweak Zjj production – Unfolded differential σ

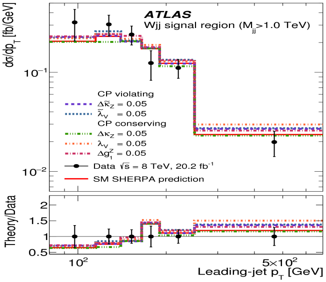
- Unfolding performed at $8\,\mathrm{TeV}$ in all analysis regions via bayesian iterative technique, for both EW and QCD+EW Zjj productions, and for single lepton flavor
- Measured for observables distinguishing between 2 leading jets and between EW/QCD Zjj (e.g., M_{jj}, $|\Delta y(j_1, j_2)|$, $|\Delta\Phi(j_1, j_2)|$, N_{jet}^{gap}, $p_T^{balance}$, p_T^{jj})
- Comparison to theoretical predictions from `POWHEG+PYTHIA6` and `SHERPA` v1.4.3
- Examples:
  - N_{jet}^{gap} well separates EW and QCD-Zjj productions (veto selects EW-Zjj)
  - $p_T^{balance}$ adequately described by both Zjj simulations



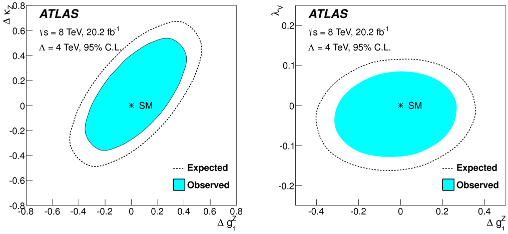


Constraints on anomalous gauge couplings

- Zjj $8\,\mathrm{TeV}$ analysis probes WWZ assuming aTGC model, using SR with $M_{jj} > 1\,\mathrm{TeV}$
- Wjj $8\,\mathrm{TeV}$ analysis probes WWV (V=Z/γ) with aTGC or EFT model using high-q^2 region (SR with $M_{jj} > 1\,\mathrm{TeV}$ and $p_T^{j_1} > 600\,\mathrm{GeV}$), which is more sensitive to anomalous couplings
- aTGC couplings simulated with `SHERPA`



- Different aTGC suppression scales (Λ) tested: $4\,\mathrm{TeV}$ (Wjj only), $6\,\mathrm{TeV}$ (Zjj only), and ∞ (both analyses, with Wjj one being more sensitive)
- aTGC couplings probed: g_1^Z and κ_Z (=1 in SM), λ_V, and $\tilde{\kappa}_Z$, $\tilde{\lambda}_V$



(Wjj analysis)

Conclusion

- EW-Zjj production cross sections have been measured at $\sqrt{s} = 7$, 8, and $13\,\mathrm{TeV}$, while EW-Wjj production cross sections have been determined at 7 and $8\,\mathrm{TeV}$
- Accurate data-driven techniques have been used to make the measurements with suppressed systematic uncertainties on QCD-Wjj(Zjj) productions
- Unfolded differential production cross sections have been estimated for EW-Wjj(Zjj) processes at $\sqrt{s} = 8\,\mathrm{TeV}$
- Stringent constraints have been put on triple-gauge-boson anomalous couplings, complementarily to WW production results
- For more information: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

BACKUP

Constraints on anomalous couplings

- Limit on a given coupling assumes all others are 0
- EFT limits on coefficients divided by new scale Λ (Wjj analysis $8\,\mathrm{TeV}$):

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

- aTGC interval limits on couplings for different scales:

Wjj analysis ($8\,\mathrm{TeV}$):

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

Zjj analysis ($8\,\mathrm{TeV}$):

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	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$