Measurements of Vector Boson Fusion With The ATLAS Detector

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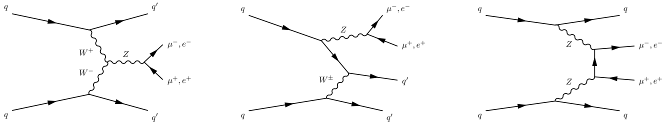
Introduction

- SM electroweak theory predicts self interaction of EWK gauge bosons.
- The self interaction of these boson in triple and quartic gauge boson couplings provides us with important tool to test SM.
  - Unitarization of the Higgs boson.
  - Background for new physics searches.
  - aTGC's and aQGC's to test new physics.
- In this presentation we are going to present production of:
  - $Wjj \to \ell\nu jj$
  - $Zjj \to \ell\ell jj$
- Large cross-section of vector boson fusion allows us to test triple gauge couplings with high precision.

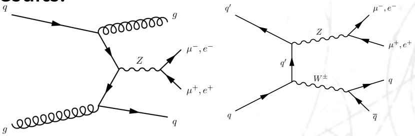
Measurement of the Electroweak Zjj

STDM-2016-09 and JHEP 04 (2014) 031



EWK Zjj production.

- There are different processes that can generate the Zjj.
- This analysis puts constraints on the productions of Zjj by:
  - Strong
  - EW VBF, Z bremstrahlung and non-resonant.
- The interference between the two channels is minimal.
- In this presentation we are going to focus on 13 TeV results in comparison with the 8 TeV results.



Strong Zjj production.

Modeling

STDM-2016-09 and JHEP 04 (2014) 031

13 TeV Analysis

- The analysis has been conducted at $\sqrt{(s)} = 13$ TeV with $\int Ldt = 3.2$ fb^{-1}
- PowHeg Box (NLO) and Sherpa (LO) are used for EWK modeling.
- Sherpa (NLO), ALPGEN (LO) and MadGraph_aMC@NLO (NLO) are used for QCD modeling.

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8 TeV Analysis

- The analysis has been conducted at $\sqrt{(s)} = 8$ TeV with $\int Ldt = 20.3$ fb^{-1}
- PowHeg Box (NLO) and Sherpa (LO) are used for strong and EWK theoretical predictions.

Search Method

STDM-2016-09 and JHEP 04 (2014) 031

13 TeV Fiducial Regions

- **Baseline** is the inclusive Signal that contains all other fiducial regions.
- **EWK-enriched** Enhances the EWK contribution by p_T^{balance} and 0 central jets
- **QCD-enriched** Enhances the QCD contribution by p_T^{balance} and at least one central jet

EWK sensitive region

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

$$p_T^{\text{balance}} = \frac{|\vec{p_T}^{\ell 1} + \vec{p_T}^{\ell 2} + \vec{p_T}^{j1} + \vec{p_T}^{j2}|}{|\vec{p_T}^{\ell 1}| + |\vec{p_T}^{\ell 2}| + |\vec{p_T}^{j1}| + |\vec{p_T}^{j2}|}$$

EWK sensitive cuts

QCD Enriching Cuts

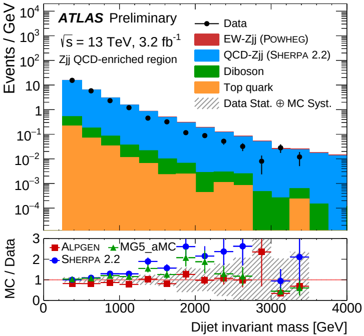
8 TeV Fiducial Regions

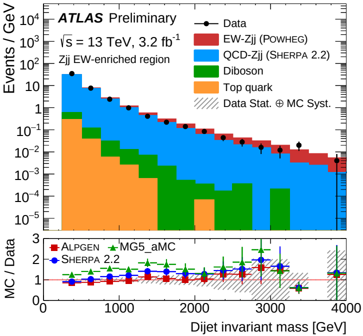
- It is really similar to 13 TeV with different names.
- QCD-enriched $\rightarrow$ Control region , EW-enriched $\rightarrow$ Search region

Inclusive (EWK+QCD) Results

Meas. of the Electroweak Zjj at 13 TeV, STDM-2016-09

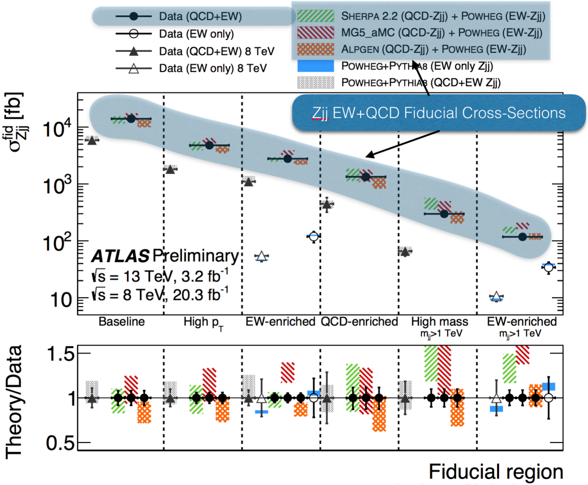
- Zjj with EWK+QCD fiducial x-sections are measured using $\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\int L dt \cdot C}$
- Good agreement with theory among all regions.
- X-sections are measured in ee and $\mu\mu$ channels and found compatible.
- The primary uncertainties are jet energy scale and resolution.
- We observe a shape discrepancy in m_{jj} distribution due to QCD-Zjj mis-modeling.
    - This is corrected while calculating fiducial x-sections.





Inclusive (EWK+QCD) Results

Meas. of the Electroweak Zjj at 13 TeV, STDM-2016-09



- Good agreement between theory and observation
- The other data points will be explained later.

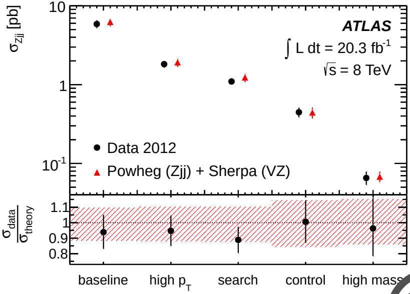
Inclusive (QCD+EWK) Results

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031

- The 8 TeV inclusive results are obtained in the same way as 13 TeV.
- Similar same m_{jj} problem are observed.
- The primary uncertainties are jet energy scale and resolution.
- Good agreement with theory among all regions.

Fiducial region	σ_{fid} (pb)
baseline	5.88 ± 0.01 (stat) ± 0.62 (syst) ± 0.17 (lumi)
high-p_T	1.82 ± 0.01 (stat) ± 0.17 (syst) ± 0.05 (lumi)
high-mass	0.066 ± 0.001 (stat) ± 0.012 (syst) ± 0.002 (lumi)
search	1.10 ± 0.01 (stat) ± 0.09 (syst) ± 0.03 (lumi)
control	0.447 ± 0.004 (stat) ± 0.059 (syst) ± 0.013 (lumi)

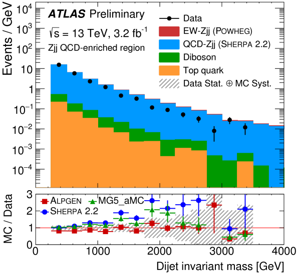
Fiducial region	σ_{theory} (pb)
baseline	6.26 ± 0.06 (stat) $^{+0.50}_{-0.60}$ (scale) $^{+0.29}_{-0.35}$ (PDF) $^{+0.19}_{-0.25}$ (model)
high-p_T	1.92 ± 0.02 (stat) $^{+0.17}_{-0.20}$ (scale) $^{+0.09}_{-0.10}$ (PDF) $^{+0.05}_{-0.07}$ (model)
high-mass	0.068 ± 0.001 (stat) $^{+0.009}_{-0.009}$ (scale) $^{+0.004}_{-0.003}$ (PDF) $^{+0.004}_{-0.002}$ (model)
search	1.23 ± 0.01 (stat) $^{+0.11}_{-0.13}$ (scale) $^{+0.06}_{-0.07}$ (PDF) $^{+0.03}_{-0.04}$ (model)
control	0.444 ± 0.005 (stat) $^{+0.051}_{-0.054}$ (scale) $^{+0.021}_{-0.025}$ (PDF) $^{+0.032}_{-0.034}$ (model)

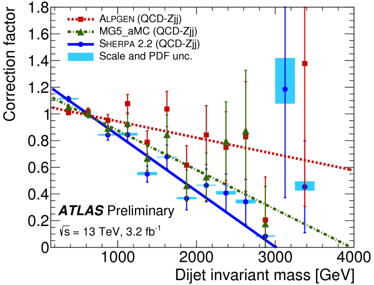


m_{jj} Shape Corrections

Meas. of the Electroweak Zjj at 13 TeV, STDM-2016-09

- QCD-enriched and EWK-enriched regions are designed to be kinematically similar.
- In order to correct the m_{jj} shape mismatch
  - On the QCD-enriched region, the background is removed.
  - Corrections to Wjj-QCD are extracted.
  - Applied to EWK-enriched region.
- Linear fit was used for the data-driven correction.
- The difference between quadratic and linear fits are found to be minimal.

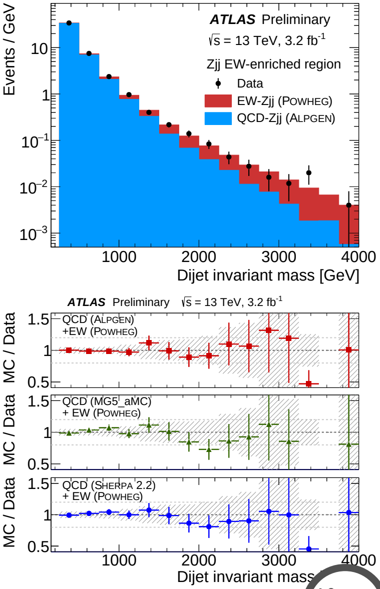




EWK Zjj Measurement

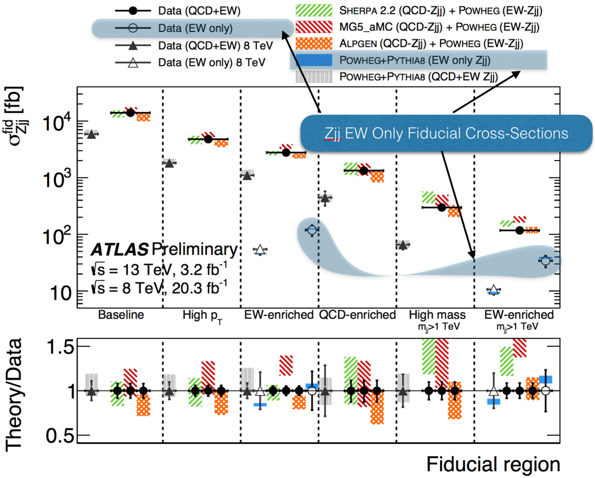
Meas. of the Electroweak Zjj at 13 TeV, STDM-201[illegible]

- Zjj EWK contribution is extracted on m_{jj}
- It's extracted on EWK-enriched region.
- Binned likelihood fit of QCD & EWK m_{jj} templates are used.
- The QCD-background shape in EWK-enriched is corrected using a data driven method.
- The cut $m_{jj} > 1$ TeV is used to enhance the signal to background ratio by 26%.
- The largest uncertainty is the QCD modeling uncertainty.



EWK Zjj Measurement

Meas. of the Electroweak Zjj at 13 TeV, STDM-2016-09

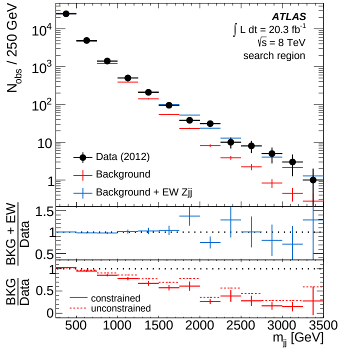


- **We observe a good agreement with the theory.**

EWK Zjj Measurement

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031

- Zjj EWK contribution is extracted on m_{jj} distribution inside the search region.
- The control region is used for estimating and constraining the background shape using re-weighting.
- PowHeg signal and data has good agreement.
- **The background only hypothesis is rejected $> 5\sigma$**



Obs:

$\sigma_{\text{EWK}} = 54.7 \pm 4.6(\text{stat})^{+9.8}_{-10.4}(\text{syst}) \pm 1.5(\text{lumi})$ fb

Exp:

$\sigma_{\text{EWK}} = 46.1 \pm 0.2(\text{stat})^{+0.3}_{-0.2}(\text{scale}) \pm 0.8(\text{pdf}) \pm 0.5(\text{model})$ fb

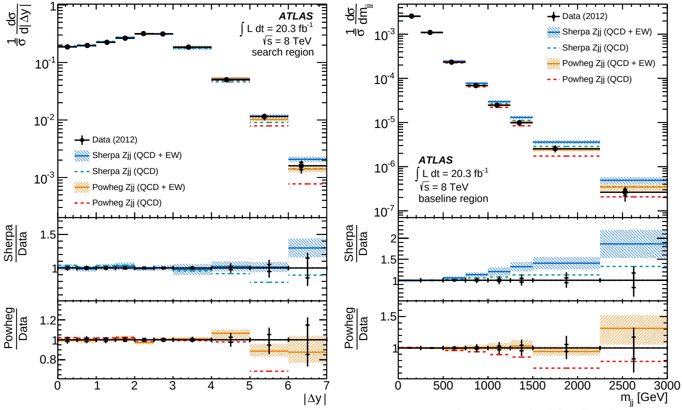
Differential Results

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031

- Some of the considered differential observables are:
  - m_{jj} ,$|\Delta y|$, $|\Delta\phi(j,j)|$, $N_{\text{jet}}^{\text{gap}}$, p_T^{balance}
- To get the differential distribution in particle level.
  1. In differential distribution, BG is subtracted from data.
  2. Bayesian unfolding is then applied to get particle level distribution.
- PowHeg has better agreement in baseline as it's NLO.
- On search region both PowHeg and Sherpa have good agreements.

Differential Plots

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031



- On both plots we can observe that high $|\Delta Y|$ and M_{jj} is sensitive to EWK.
- On the M_{jj} differnatial we can observe modelling problems.
- None off the generators can fully describe the modeling.
- We have good agreement with prediction.

aTGC Results

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031

- Effective lagrangian has been used to set limits on aTGC

$$\frac{\mathcal{L}}{g_{WWZ}} = i[g_{1,Z}(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}) + K_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m^2_W}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}]$$

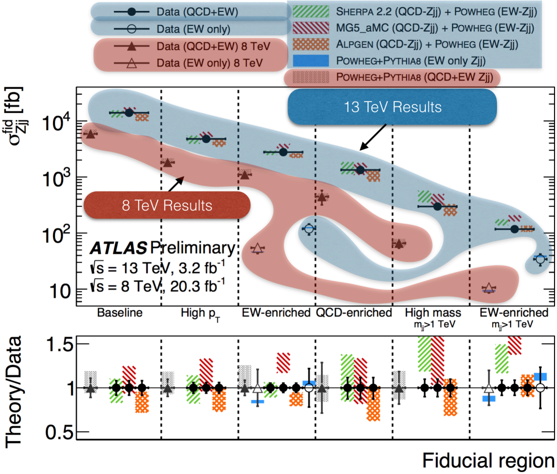
- aTGC limits have been set on search region with $m_{jj} > 1$ TeV
- To preserve unitarity a form factor is used , $\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}^2/\Lambda^2)^2}$, where α is anomalous coupling of interest.
- Two scales have been used. ($\Lambda = 6$ TeV, ∞)

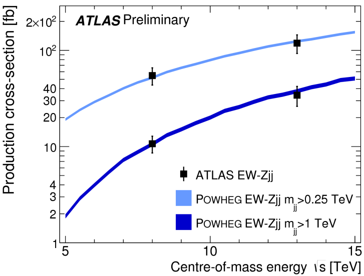
aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

EWK Zjj Measurement Summary

Measurement of the Electroweak Zjj

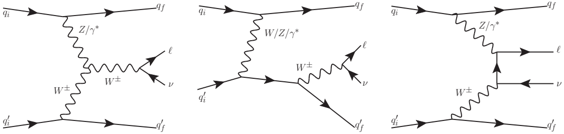
Overall all measurements are in good agreement with the theory.





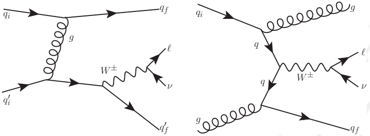
Measurement of the Electroweak Wjj

Eur. Phys. J. C (2017) 77:474



EWK Wjj production.

- Similar to VBF Zjj prod., Wjj prod. is composed of:
  - Strong
  - EWK VBF, W bremstrahlung and non-resonant.
- Similar to Zjj, Wjj EWK contribution increases with m_{jj}.



Strong Wjj production.

Modeling

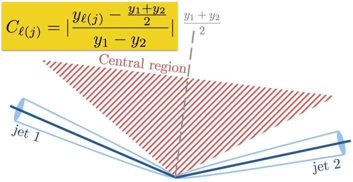
Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

- Wjj **is simulated using PowHeg + Pythia8 (NLO) with data driven corrections.**
- Sherpa (LO) is also used to validate the signal as well to estimate the uncertainty of interference between strong and EWK channels.
- For testing unfolded distributions, HEJ (High Energy Jets)(all-order) is also used.
- The BG with prompt charged leptons are modeled with MC.
- The multi-jet background is estimated using a data-driven method.
- The analysis has been conducted at both $\sqrt(s) = 7, 8$ TeV with $\int Ldt = 4.7, 20.3$ fb^{-1}
  - This is the only VBF measurement at 7 TeV.

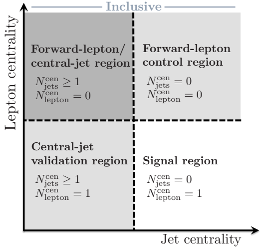
Search Method

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

- The analysis has been split into 3 fiducial regions for setting fiducial cross-section limits. Marked Blue.
- 6 additional fiducial regions have been implements for differential measurements. Marked Red.
- There is a fiducial region defined to enhance aTGC's production.



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

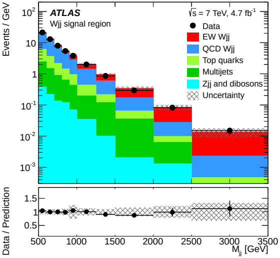


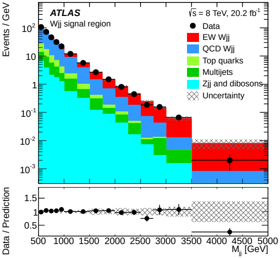
EWK Wjj Measurement

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017)

- Using the m_{jj} distribution on the signal region, the fiducial EWK Wjj cross-section was measured.
- The primary uncertainties, jet energy scaling and resolution.
- Similar to Zjj, m_{jj} shape correction has been driven for QCD-Wjj contribution in forward-lepton control region, The slopes of the fit were consistent with 0.
- The cross-sections are extracted using a binned likelihood fit on m_{jj} distributions in the signal region.

$\sqrt{s}$	$\sigma^{\text{fid}}_{\text{meas}}$ [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





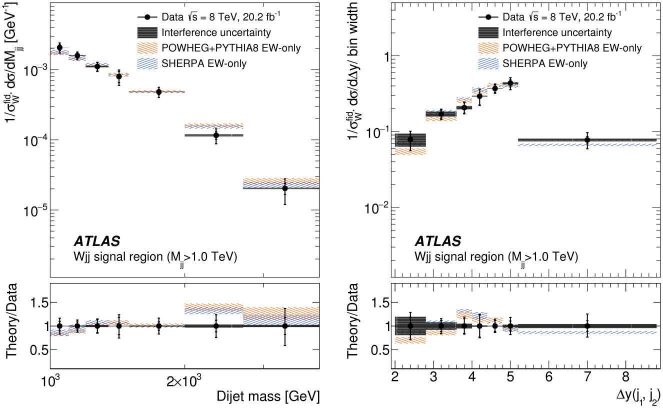
Differential Measurements

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

- The differential measurements are only done for 8 TeV.
- Differential measurements are done in all nine fiducial regions.
- EWK differential measurements require $m_{jj} > 1$ TeV
  - For EWK differential measurements, before unfolding in addition to background, QCD Wjj is also removed.
- The considered observables that are EWK sensitive:
  - C_ℓ, C_j, M_{jj}, $\Delta y(j_1, j_2)$, $N_{\text{jets}}^{\text{gap}}$
- The considered observables that are aTGC sensitive:
  - $p_T^{j_1}, p_T^{jj}, \Delta\phi(j_1, j_2)$

Differential EWK cross section

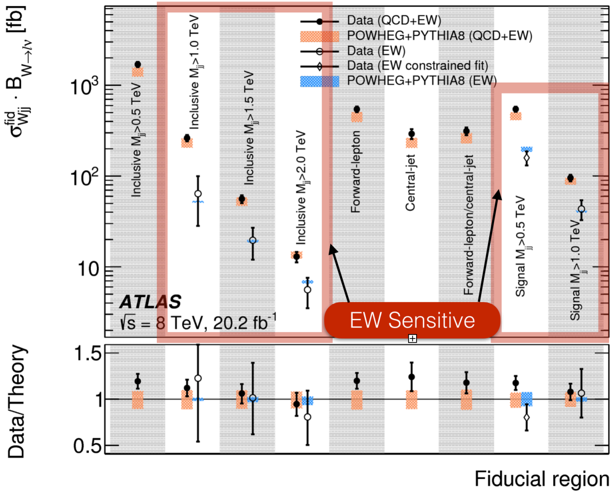
Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474



- The over estimation on m_{jj} cannot be seen here.
- Interference effects becomes much more dominant on low $|\Delta Y|$.
- Differential cross section measured for EW-Only Wjj processes in various fiducial regions in agreement with prediction.

Integrated Differential Cross-Sections

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474



- Integrated cross-sections are also extracted from each fiducial region.
- Each region has good agreement with theory.

aTGC Results

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

- Limits on aTGC are set with the fiducial region $m_{jj} > 1$ TeV, $N_{\ell}^{\text{cen}} = 1$, $N_{j}^{\text{cen}} = 0$, $p_T^{j1} > 600$ GeV.
- 39 Events were predicted and 30 events were observed.
- The aTGC's were modeled using the following effective Lagrangian.
- aTGC limits of 95% CL is set.

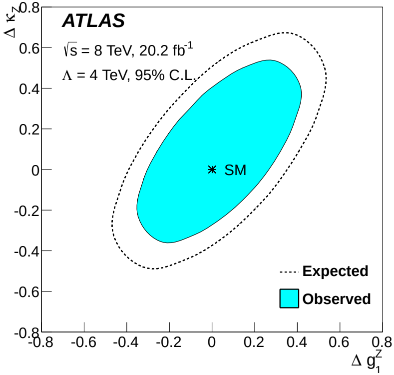
$$i\mathcal{L}_{\text{eff}}^{WWW} = g_{WWW}\{[g_1^V V^{\mu}(W_{\mu\nu}^{-}W^{+\nu} - W_{\mu\nu}^{+}W^{-\nu}) + K_V W_{\mu}^{+}W_{\nu}^{-}V^{\nu\mu} + \frac{\lambda_V}{m_W^2}V^{\mu\nu}W_{\nu}^{+\rho}W_{\rho\mu}^{-}]$$
$$-[\frac{\widetilde{K_V}}{2}W_{\mu}^{-}W_{\nu}^{+}\epsilon^{\mu\nu\rho\sigma}V_{\rho\sigma} + \frac{\widetilde{\lambda_V}}{2m_W^2}W_{\rho\mu}^{-}W_{\nu}^{+\mu}\epsilon^{\nu\rho\alpha\beta}V_{\alpha\beta}]\}$$

- To preserve unitarity a form factor is used , $\alpha(q^2) = \frac{\alpha}{(1+q^2/\Lambda^2)^2}$, where α is anomalous coupling of interest.
- Two scales have been used.($\Lambda = 4\,$TeV, ∞)

aTGC Results

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

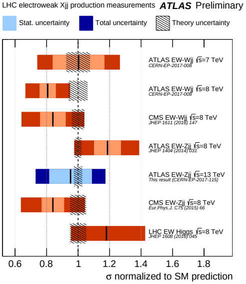
	$\Lambda = 4$ TeV		$\Lambda = \infty$	
	Expected	Observed	Expected	Observed
Δg_1^Z	$[-0.39, 0.35]$	$[-0.32, 0.28]$	$[-0.16, 0.15]$	$[-0.13, 0.12]$
$\Delta\kappa_Z$	$[-0.38, 0.51]$	$[-0.29, 0.42]$	$[-0.19, 0.19]$	$[-0.15, 0.16]$
λ_V	$[-0.16, 0.12]$	$[-0.13, 0.090]$	$[-0.064, 0.054]$	$[-0.053, 0.042]$
$\tilde{\kappa}_Z$	$[-1.7, 1.8]$	$[-1.4, 1.4]$	$[-0.70, 0.70]$	$[-0.56, 0.56]$
$\tilde{\lambda}_V$	$[-0.13, 0.15]$	$[-0.10, 0.12]$	$[-0.058, 0.057]$	$[-0.047, 0.046]$

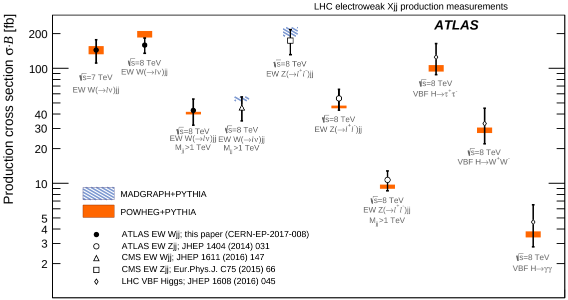


- Limits on aTGC are set with 95% CL.
- Conversion to effective field theory are also available.

Summary

- Understanding of the EWK process is crucial for our understanding and testing of SM.
- Detailed EWK VBF studies have been conducted for $8,\ 13$ TeV Zjj and $7,\ 8$ TeV Wjj.
- Differential cross-sections and aTGC limits are available at 8 TeV studies for both productions.
- **Overall good agreement is found between data and predictions.**



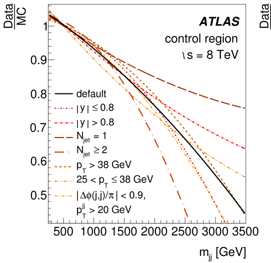


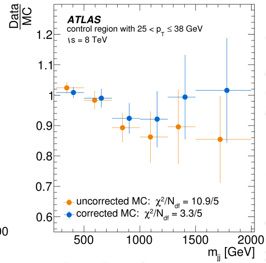
Backup Slides

m_{jj} Shape Corrections

Measurement of the Electroweak Zjj at 8 TeV, JHEP 04 (2014) 031

- Control and search regions are designed to be kinematically similar.
- In order to correct the m_{jj} shape mismatch, corrections to Wjj-QCD are extracted in control region and applied to search region.
- First order poly. was used for the data-driven correction.
- The difference between second order poly. and first order poly. are found to be minimal.





m_{jj} Shape Corrections

Measurement of the Electroweak Wjj, Eur. Phys. J. C (2017) 77:474

- Control and signal regions are designed to be kinematically similar
- In order to correct the m_{jj} shape mismatch, corrections to Wjj-QCD are extracted in control region and applied to search region.
- First order poly. was used for the data-driven correction.
- The effect of slope correction of 1%/TeV is approx 0.1 in μ_{EW}.