

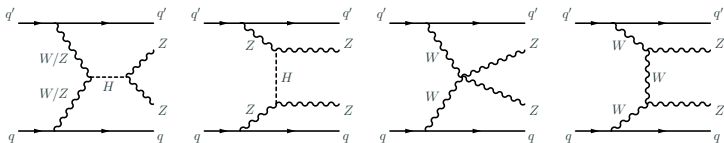
OBSERVATION OF ELECTROWEAK PRODUCTION OF TWO JETS AND A Z-BOSON PAIR WITH THE ATLAS DETECTOR

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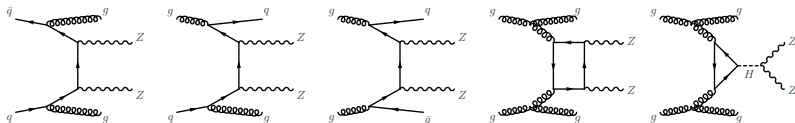
- Vector Boson Scattering process is crucial for probing the mechanism of electroweak symmetry breaking in the Standard Model
- The study of VBS process is sensitive to triple and quartic gauge couplings
- The SM Higgs contribution to the vector boson scattering process ensures the unitarity of the scattering matrix
- Typical diagrams for the electroweak production of $ZZjj$ ¹:



¹link: [arxiv: 2004.10612](https://arxiv.org/abs/2004.10612)

Process	ATLAS	CMS	
$W^\pm W^\pm$	6.5 (4.4) σ^2 PRL (2019)	5.5 (5.7) σ PRL (2018)	golden channel, large ratio of the EW to the QCD production
WZ	5.3 (3.2) σ PLB (2019)	6.8 (5.3) σ PLB (2020)	similar cross-section as $W^\pm W^\pm$, but larger QCD background
ZZ	5.5 (4.3) σ arxiv: 2004.10612	4.0 (3.5) σ PLB (2021)	an experimental challenge

- The $ZZjj$ process has the smallest cross section
- Large QCD background compared to a small electroweak signal



²observed (expected) significance

- ATLAS full Run 2 dataset, luminosity 139 fb^{-1}
- Signal modeling: MadGraph + Pythia
- Include both $lllljj$ and $ll\nu\nu jj$ channels
 - $lllljj$ channel is clean without other background contamination. Irreducible QCD $ZZjj$ is the major background
 - $ll\nu\nu jj$ channel has a larger branching ratio and complements the $lllljj$ channel.
- Experimental signature:
 - 4 leptons, or 2 leptons with E_T^{miss}
 - two forward/backward jets
- Gradient Boosted Decision Tree (BDTG) is used to separate the signal and backgrounds
- link for this analysis: [arxiv: 2004.10612](https://arxiv.org/abs/2004.10612)

EVENT SELECTIONS AND YIELDS

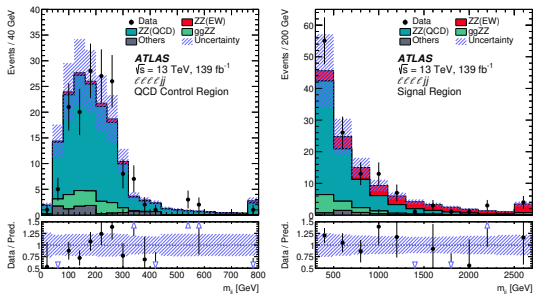
- Signal region selections:

Objects	$lllljj$	$ll\nu\nu jj$
Leptons	$p_T(\ell) > 20/20/10/7$ GeV, $ \eta(\mu) < 2.7$, $ \eta(e) < 2.47$ $66 < m_{\ell\ell} < 116$ GeV, $\Delta R(\ell\ell) > 0.2$	$p_T(\ell) > 30/20$ GeV, $ \eta(\ell) < 2.5$ $80 < m_{\ell\ell} < 100$ GeV
Jets	$p_T(j) > 40/30$ GeV, $ \eta(j) < 4.5$ $m_{jj} > 300$ GeV, $\Delta y_{jj} > 2$ $y(j_1) \times y(j_2) < 0$	$p_T(j) > 60/40$ GeV, $ \eta(j) < 4.5$ $m_{jj} > 400$ GeV, $\Delta y_{jj} > 2$ $y(j_1) \times y(j_2) < 0$, b-jet veto
E_T^{miss}	-	E_T^{miss} -significance > 9

- Event yields in the signal regions:

Process	$lllljj$	$ll\nu\nu jj$
EW ZZj	20.6 ± 2.5	12.3 ± 0.7
QCD ZZj	77 ± 25	17.2 ± 3.5
QCD ggZZj	13.1 ± 4.4	3.5 ± 1.1
Non-resonant- $\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

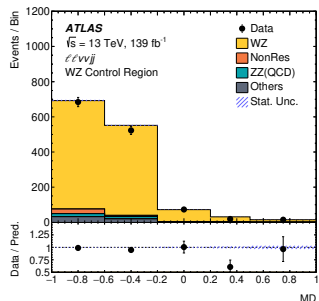
BACKGROUND ESTIMATION IN $lllljj$ CHANNEL



- QCD $ZZjj$ process is estimated using a QCD control region by reversing di-jet selections, $m_{jj} < 300$ GeV or $\Delta y_{jj} < 2$
 - the kinematics of QCD $ZZjj$ process is validated in an EW-suppressed control region by requiring the centrality > 0.5 for at least one of the Z bosons
- Small contributions (less than 3%) include:
 - Z + jets, top-quark and $WZjj$ events with misidentified leptons, estimated from data
 - minor background contributions from VW and ttV production, estimated from MC simulation

- QCD ZZjj process, estimated from MC simulation
- three lepton control region (3ℓCR)
 - the normalization of WZ process is constrained in 3ℓCR with WZ purity $\sim 92\%$
 - Scale factor

$$sf_{WZ} = (\text{Observed} - \text{Non_WZ}_{MC}) / WZ_{MC}$$



- $e\mu$ control region ($e\mu$ CR)
 - Estimate contributions from $t\bar{t}$, WW , Wt processes with data-driven method
 - Select one $e\mu$ pair with the rest signal region selections
 - Define $\epsilon = \sqrt{N_{ee}^{\text{data}} / N_{\mu\mu}^{\text{data}}}$ as the reconstruction efficiency difference between electrons and muons
 - Contamination in the SR: $N_{ee}^{\text{bkg}} = \frac{1}{2} \times \epsilon \times N_{e\mu}^{\text{data}}, N_{\mu\mu}^{\text{bkg}} = \frac{1}{2} \times \frac{1}{\epsilon} \times N_{e\mu}^{\text{data}}$

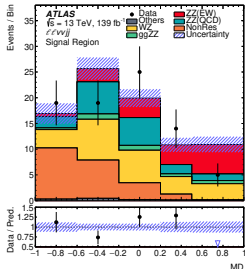
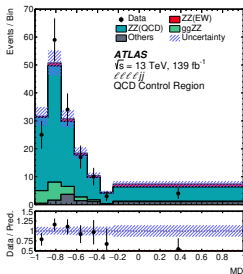
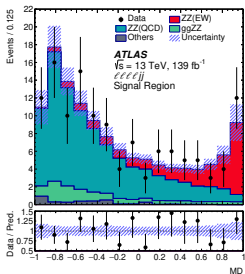
SYSTEMATIC UNCERTAINTIES

- Experimental uncertainties $\sim 10\%$ (5%) in $lllljj$ ($ll\nu\nu jj$) channel
 - luminosity
 - energy measurements of leptons and jets
 - the lepton reconstruction and selection efficiencies
- uncertainties from non-ZZjj backgrounds $\sim 15\%$
- Theoretical uncertainties

	Process	PDF (%)	α_S (%)	QCD scale (%)	Parton shower (%)
Signal Region					
	EW $lllljj$	+5.9 -5.9		+6.1 -5.6	± 3.3
	QCD $lllljj$	+2.0 -1.0	+2.6 -2.6	+34.2 -22.8	
	EW $ll\nu\nu jj$	± 2.0		± 2.0	
	QCD $ll\nu\nu jj$	± 1.3	± 2.6	± 19.6	
QCD Control Region					
	EW $lllljj$	± 6.1		+0.8 -1.1	± 10.1
	QCD $lllljj$	+2.0 -1.0	± 2.6	+31.5 -22.0	

MULTIVARIATE ANALYSIS

- Multivariate discriminants (MD) based on BDTG algorithm are trained
- lepton, jet related variables are used in the training



Rank	$lllljj$ variables	$llvvlj$ variables
1	m_{jj}	$\Delta\eta_{ee}$
2	p_T^1	m_{ee}
3	p_T^2	$\Delta\phi_{ee}$
4	p_T^{ZZij} / H_T^{ZZij}	m_{jj}
5	$Y_{j1} \times Y_{j2}$	E_T^{miss} -significance
6	$\Delta\eta_{jj}$	Δy_{jj}
7	Y_{ZZ}^*	$Y_{j1} \times Y_{j2}$
8	Y_{Z1}^*	H_T^{ZZij}
9	p_T^{ZZ}	ΔR_{ee}
10	m_{ZZ}	p_T^2
11	p_T^{Z1}	E_T^{miss}
12	$p_T^{\ell 3}$	$p_T^{\ell 2}$
13	$p_T^{\ell 1}$	-

- The profile likelihood ratio is used as a test statistic in $lllljj$, $ll\nu\nu jj$, and combined channel
- MD is chosen to be the discriminant variable
- QCD ZZjj control region in $lllljj$, signal regions in $lllljj$ and $ll\nu\nu jj$ are used in the fit. The strength of QCD ZZjj $\mu_{\text{QCD}}^{lllljj}$ is 0.95 ± 0.22
- the EW signal is extracted from the MD distribution:

	EW Signal Strength μ_{EW}	Significance Obs. (Exp.)
$lllljj$	1.5 ± 0.4	$5.5 (3.9) \sigma$
$ll\nu\nu jj$	0.7 ± 0.7	$1.2 (1.8) \sigma$
Combined	1.35 ± 0.34	$5.5 (4.3) \sigma$

MEASUREMENT OF FIDUCIAL CROSS-SECTIONS

- the cross-sections for the production of inclusive $ZZjj$ (EW+QCD) are measured
- Fiducial volume definition: mimic the detector-level signal region selections

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E_T^{miss}	-	$E_T^{\text{miss}} > 130$ GeV

Fiducial Cross-section σ [fb]

Measurements

$$lllljj \quad 1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$$

$$ll\nu\nu jj \quad 1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$$

Predictions

$$lllljj \quad 1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$$

$$ll\nu\nu jj \quad 1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$$

- the production of electroweak $ZZjj$ is observed with ATLAS Run2 data (139 fb^{-1}), with observed (expected) significance of 5.5 (4.3) σ
- Inclusive cross-sections for $lllljj$ and $ll\nu\nu jj$ are measured in dedicated fiducial volumes. The measurement results are consistent with the Standard Model prediction
- link for this analysis: [arxiv: 2004.10612](https://arxiv.org/abs/2004.10612)