PROCEEDINGS OF SCIENCE

Vector boson scattering, triple gauge-boson final states and limits on anomalous quartic gauge couplings with the ATLAS detector

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Measurements of the cross sections of the production of three electroweak gauge bosons and of vector-boson scattering processes at the LHC constitute stringent tests of the electroweak sector of the Standard Model and provide a model-independent means to search for new physics at the TeV scale. The ATLAS collaboration has recently searched for the production of three W bosons or of a W boson and a photon together with a Z or W boson at a center of mass energy of 8 TeV. We also present searches for the electroweak production of a Z boson and a photon together with two jets. The results are compared to state-of-the art theory predictions and have been used to constrain anomalous quartic gauge couplings.

The European Physical Society Conference on High Energy Physics
5-12 July
Venice, Italy

*Speaker.

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PoS(EPS-HEP2017)448

ATL-PHYS-PROC-2017-160
27/09/2017

1. Introduction

The productions of two vector bosons ($WW, WZ, ZZ, Z/W+\gamma$) are important processes for probing the $SU(2)_L \times U(1)_Y$ gauge symmetry of the electroweak (EWK) theory that predicts the self-couplings of the vector bosons. In particular, it is critical to test the triple and quartic gauge-boson couplings (TGCs and QGCs) independently, since new physics could generate additional contributions to QGCs with respect to the Standard Model (SM) predictions [1, 2, 3, 4], but without significant impact on the TGCs [5]. Cross section measurements of vector-boson scattering (VBS), $VV \to VV$ ($V = W/Z/\gamma$), provide a direct test of QGCs. Triboson production cross section measurement is also sensitive to probe QGCs. To search for deviations from the SM QGCs, a parameterised framework of anomalous quartic gauge couplings (aQGCs) is used in our analyses.

A variety of measurements involving the VBS and QGCs have been performed at the ATLAS experiment [6] at the LHC, as illustrated in Figure 1. This report focuses on the VBS measurement with $Z\gamma$ plus 2 jets [7] and studies on triboson productions, WWW [8] and $WV\gamma$ ($V = W/Z$) [9].

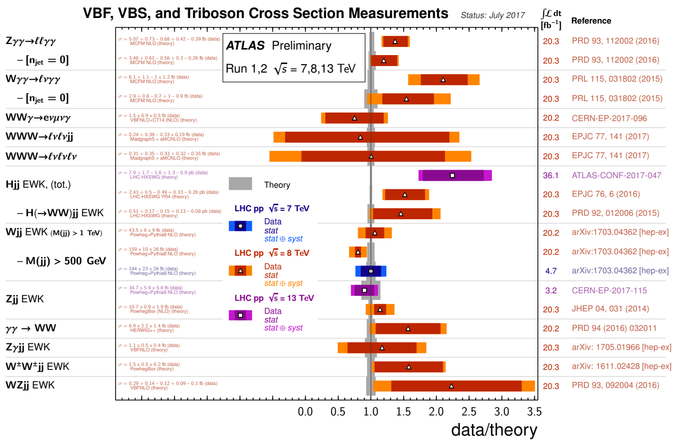


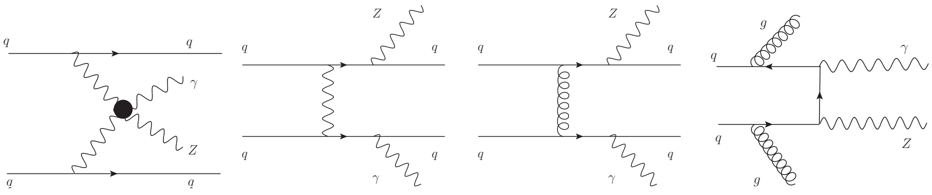
Figure 1: The data/theory ratio for several vector boson fusion, vector boson scattering, and triboson fiducial cross section measurements, corrected for leptonic branching fractions [10].

2. Experimental strategy

The two main processes relevant for aQGC measurements are VBS and triboson production. Various channels are available with distinct experimental signatures, depending on the type and decay channel of the produced vector bosons (W, Z or γ). In general, fiducial cross sections are measured first in search region (SR) for either the VBS or triboson processes. Then more sensitive regions for QGCs measurements are defined to search for aQGCs.

3. VBS with $Z\gamma$ plus two jets final state

The $Z\gamma jj$ EWK production contains processes with fourth-order EWK coupling $\mathscr{O}(\alpha_{EM}^4)$. These include both VBS and non-VBS diagrams. The same final state can also come from QCD



(a) (b) (c) (d)

Figure 2: Feynman diagrams of (a) electroweak $Z\gamma jj$ production involving VBS subprocesses, (b) electroweak $Z\gamma jj$ production involving non-VBS subprocesses, (c) QCD $Z\gamma jj$ production with gluon exchange, (d) QCD $Z\gamma jj$ production with gluon radiation.

processes with second-order EWK coupling and second-order QCD coupling $\mathscr{O}(\alpha_{EM}^2\alpha_s^2)$. The Feynman diagrams for those processes are shown in Figure 2.

Experimentally, $Z\gamma jj$ EWK processes are characterized by the production of two energetic hadronic jets with wide rapidity separation and large dijet invariant mass. The vector-boson pair is typically produced more centrally than in non-EWK processes. Two channels of Z boson decays to di-leptons and di-neutrinos are used in the measurement.

In the charged-lepton channel, $\ell^+\ell^-\gamma jj$ events are required to have one photon candidate with transverse energy $E_{\mathrm{T}}^{\gamma} > 15$ GeV, a pair of same-flavour leptons (electrons or muons) with opposite-sign (OS), and at least two reconstructed jets. The invariant mass of the two leptons must be greater than 40 GeV. The sum of the dilepton mass and the three-body $\ell\ell\gamma$ invariant mass is required to be larger than 182 GeV. The SR is defined by requiring $m_{jj} > 500$ GeV. Finally, the sensitive region for aQGC search is defined by requiring events in the SR to have a photon with $E_{\mathrm{T}}^{\gamma} > 250$ GeV.

In the neutrino channel, $\nu\bar{\nu}\gamma jj$, the Z boson signature is a large missing transverse momentum from the undetected neutrino pair. Therefore, events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV and one photon with $E_{\mathrm{T}}^{\gamma} > 150$ GeV and at least two jets. In addition, a lepton veto requirement is applied to reduce the large contribution from $W(\rightarrow \ell\nu)\gamma+$ jets events. A set of angular selection criteria are also applied based on event topology to suppress the large background from $\gamma+$ jets. To maximize the sensitivity to search for aQGC, it is required that photon centrality (Equ. 3.1) must be smaller than 0.3, and momentum balance of the $\nu\bar{\nu}\gamma jj$ object ($|\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\gamma} + \vec{p}_{\mathrm{T}}^{j1} + \vec{p}_{\mathrm{T}}^{j2}|/(E_{\mathrm{T}}^{\mathrm{miss}} + |\vec{p}_{\mathrm{T}}^{\gamma}| + |\vec{p}_{\mathrm{T}}^{j1}| + |\vec{p}_{\mathrm{T}}^{j2}|)$) must be smaller than 0.1, and dijet invariant mass must be greater than 600 GeV.

The fiducial cross section is measured using the charged-lepton channel events, by fitting the centrality observable ζ:

$$\zeta \equiv \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}}, \quad where \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}, \tag{3.1}$$

here η is the pseudorapidity of the physics object.

The measured cross section is 1.1 ± 0.5 (stat) ± 0.4 (syst) fb, consistent with the NLO SM prediction of 0.94 ± 0.09 fb, which corresponds to a signal significance of 2σ.

The limit on aQGCs is extracted using events from both charged-lepton and neutrino channels in the aQGC region. The results are shown in Table 1 and are comparable with available CMS $Z(\rightarrow \ell^+\ell^-)\gamma jj$ [11] and $W(\rightarrow \ell\nu)\gamma jj$ [12] results.

	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	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	$[-52, 52]$	$[-43, 43]$

Table 1: Measured and expected one-dimensional limits of $Z(\to \ell^+\ell^-/\nu\bar{\nu})\gamma jj$ combined channels on aQGC parameters by ATLAS [7].

$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
Preselection	Exactly three charged leptons with $p_T > 20$ GeV		
E_T^{miss}	-	$E_T^{miss} > 45$ GeV	$E_T^{miss} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	-	
Angle between trilepton and $\vec{p}_T^{miss}$	$\lvert\phi^{3\ell} - \phi^{\vec{p}_T^{miss}}\rvert > 2.5$		
Z boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$m_Z - m_{SFOS} > 35$ GeV or $m_{SFOS} - m_Z > 20$ GeV	$\lvert m_{SFOS} - m_Z\rvert > 20$ GeV
Jet veto	At most one jet with $p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$		
b-jet veto	No identified $b-$jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$		

Table 2: Selection criteria for the $\ell\nu\ell\nu\ell\nu$ channel, split based on the number of SFOS (same-flavor, opposite-sign) lepton pairs: 0 SFOS, 1 SFOS, and 2 SFOS [8].

$\ell\nu\ell\nu jj$	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$
Lepton	Exactly two same-charge leptons with $p_T > 30$ GeV		
Jets	At least two jets with $p_T(1) > 30$ GeV, $p_T(2) > 20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
E_T^{miss}	$E_T^{miss} > 55$ GeV		-
m_{jj}	$65GeV < m_{jj} < 105$ GeV		
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$		
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV	-	
Third-lepton veto	No third lepton with $p_T > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified $b-$jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$		

Table 3: Selection criteria for the $\ell\nu\ell\nu jj$ channel, split based on the lepton flavour: $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^\pm\mu^\pm$ [8].

4. Triboson WWW production

The WWW production measurement uses both $\ell\nu\ell\nu\ell\nu$ and $\ell\nu\ell\nu jj$ decay channels. The experimental signature of the $\ell\nu\ell\nu\ell\nu$ channel is the presence of three charged leptons and E_T^{miss}. The signature of the $\ell\nu\ell\nu jj$ channel is the presence of two same-charge leptons plus E_T^{miss} and two jets with an invariant mass of dijet close to 80 GeV. The selection criteria for fully and semi-leptonic channels are summarized in Table 2 and Table 3, separately.

The expected and observed fiducial cross sections are summarized in Table 4 for both channels. The observed (expected) upper limit on the fiducial cross section in the absence of $W^\pm W^\pm W^\mp$ production is found to be 1.3 fb (1.1 fb) in the $\ell\nu\ell\nu\ell\nu$ channel and 1.1 fb (0.9 fb) in the $\ell\nu\ell\nu jj$ channel. The measurement uncertainties are given in the Table.

Contributions from sources beyond the SM to the $W^\pm W^\pm W^\mp$ production process can be expressed in a model-independent way using higher-dimensional operators leading to $WWWW$ aQGCs. Results are shown in Figure 3 for cut-off values of $\Lambda_{FF} = 1$ TeV and $\Lambda_{FF} = \infty$.

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		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.286 ± 0.006 (stat.) ± 0.015 (PDF) ± 0.010 (scale)	$0.24\ ^{+0.39}_{-0.33}$ (stat.) $^{+0.19}_{-0.19}$ (syst.)
Total		241.5 ± 0.1 (stat.) $\pm$ 10.3 (PDF) $\pm$ 6.3 (scale)	230 $\pm$200 (stat.) $^{+150}_{-160}$ (syst.)

Table 4: The predicted and observed fiducial cross sections for the $\ell\nu\ell\nu\ell\nu$ and $\ell\nu\ell\nu jj$ channels and the predicted and observed total cross section for the combination of the two channels [8]. The extrapolation factor from the fiducial phase space to the total phase space is large, mainly due to the W boson decay branching ratios.

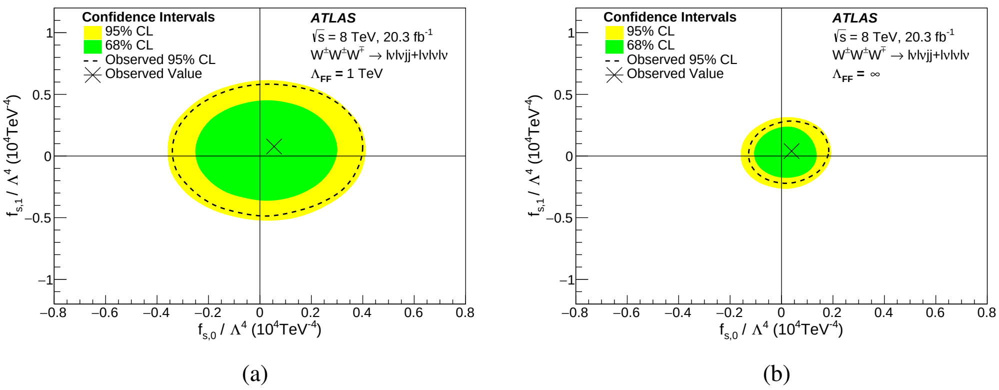


Figure 3: Expected 68% and 95% CL contours for $f_{S,1}/\Lambda^4$ vs $f_{S,0}/\Lambda^4$ compared to the observed 95% CL contour and the observed best-fit value for cases when (a) $\Lambda_{FF} = 1$ TeV and (b) $\Lambda_{FF} = \infty$ [8].

5. Triboson $WV\gamma$ production

$WV\gamma$ events in proton-proton collisions can be produced either through the $WWZ\gamma$ and $WW\gamma\gamma$ QGC vertices, or through radiation of one or more bosons. The fully leptonic final state ($e\nu\mu\nu\gamma$) of $WW\gamma$ production containing an electron, a muon, a neutrino and a photon is studied as it has a clean experimental signature. Semi-leptonic final states ($\ell\nu jj\gamma$) containing one electron or muon, a neutrino, two jets and a photon are also studied.

The fiducial region definition is summarized in Table 5, for both fully and semi-leptonic channels. Fiducial cross section is measured in fully leptonic channel as 1.5 ± 0.9 (stat) ± 0.5 (syst) fb, agrees well with prediction of 2 fb. The observed (expected) significance of this cross section is determined by evaluating the p-value of the background-only hypothesis at 95% confidence level, and corresponds to 1.4 (1.6) σ.

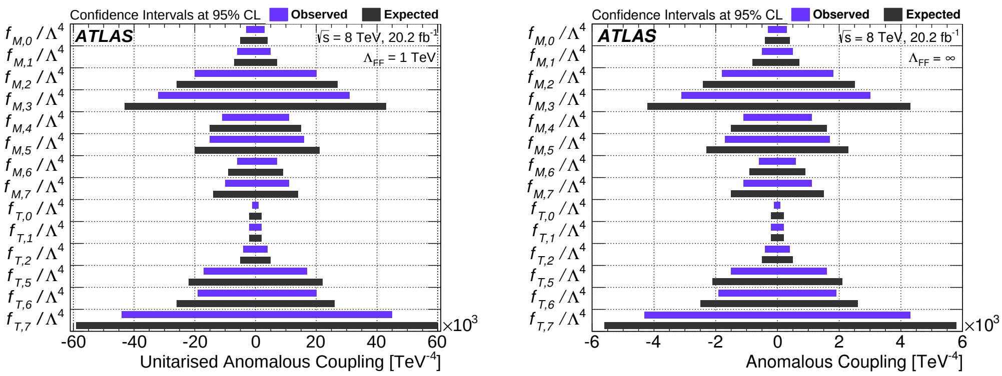
To search for aQGCs, a new fiducial region is defined by increasing the photon E_T requirement to 120 (200) GeV for fully (semi) leptonic channel and the results are summarized in Figure 4.

6. Conclusion

The VBS and triboson processes are important to test the EWK theory and are critical to test the QGCs. Various measurements have be performed at the ATLAS experiment and have provided limits on QGCs.

	Fiducial Requirements	
	$e\nu\mu\nu\gamma$	$\ell\nu jj\gamma$
Leptons	1 electron and 1 muon $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$ no 3^{rd} lepton ($p_{\mathrm{T}} > 7$ GeV) opposite charge leptons, $\Delta R(\ell,\ell') > 0.1$	1 electron or 1 muon $p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 2.5$ no 2^{nd} lepton ($p_{\mathrm{T}} > 7$ GeV)
Photon	at least one isolated photon with $E_{\mathrm{T}} > 15$ GeV and $\lvert\eta\rvert < 2.37$, $\Delta R(\ell,\gamma) > 0.5$	
Jets	$N_{jets} = 0$ $p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 4.4$	$N_{jets} \geq 2$ and $N_{b-jets} = 0$ $p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 2.5$, $\Delta\eta_{jj} < 1.2$, $\Delta R_{jj} < 3$ $70 < m_{jj} < 100$ GeV
	$\Delta R(j,\gamma) > 0.5$, $\Delta R(j,\ell) > 0.5$	
W boson	$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 15$ GeV, $m_{e\mu} > 50$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, $m_{\mathrm{T}} > 30$ GeV	

Table 5: Definition of the fiducial regions of the fully leptonic and semi-leptonic $WV\gamma$ analyses [9].



(a) (b)

Figure 4: Observed and expected confidence intervals at 95% CL on the different anomalous quartic gauge couplings for the combined WV analysis. A dipole form factor with a form factor energy scale of (a) $\Lambda_{FF} =$ 1 TeV and (b) $\Lambda_{FF} = \infty$ [9].

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