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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 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. ATLAS has also searched for the electroweak production of a heavy boson and a photon together with two jets. All results have been used to constrain anomalous quartic gauge couplings and have been compared to the latest theory predictions.

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1. Introduction

Higgs boson discovery at the LHC [1, 2] opens a new era for proving the electroweak sector. One important measurement of electroweak sector is the measurement of longitudinal scattering amplitude of the $VV \to VV$ ($V = W/Z/\gamma$) processes. Because unitarity of this processes are restored by Higgs exchange, this measurement proves one of the important role of Higgs bosons in gauge theory. Moreover, any heavy particles which are undetectable by direct resonance search can be detected by this measurement due to those particles can disturbs unitarity restoring.

While evidence of the vector boson scattering is achieved in same sign lepton final state [3], different view of measurements give more stringent knowledge of electroweak sector. In this note, latest two results, $Z\gamma jj$ final state and triboson in $WW\gamma/WZ\gamma$ final state at $\sqrt{s} = 8$TeV corresponding to an integrated luminosity of 20.2fb^{-1} recorded by the ATLAS detector [4] are introduced.

2. Vector boson scattering in $Z\gamma jj$ final state

The $Z\gamma jj$ electroweak (EWK) production ($qq \to qqZ\gamma,\ j = q/g$) contains processes with fourth-order electroweak coupling $O(\alpha_{em}^4)$. The same $Z\gamma jj$ final state can be produced by QCD-mediated processes with second-order electroweak coupling and second-order strong coupling $O(\alpha_{em}^2\alpha_s^2)$. Such processes can involve radiated gluons in the initial and/or final state as well as quark scattering processes mediated by gluons. According to the SM, a small constructive interference occurs between production of QCD and EWK quark scattering.

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. These kinematic properties are exploited to select a phase-space region where the electroweak production is enhanced with respect to the QCD mediated processes.

2.1 Event selection

Physics objects are reconstructed by algorithms commonly used in ATLAS, detail is described in [5]. Events are divided two categories, charged lepton and neutrino channel. In charged lepton channel, at least 2 leptons, 1 photon and 2 jets are required. To avoid FSR photon from electron, $m_{ll} + m_{ll\gamma} > 182$ GeV are required, 182 GeV corresponding to twice of Z boson pole mass. Control region which is required $150 < m_{jj} < 500$ GeV (m_{jj} is invariant mass of two leading jets) is defined to constrain nuisance parameters. Signal region is required $m_{jj} > 500$ GeV (called "Search region"), additionally $E_{\mathrm{T}}^{\gamma} > 250$ GeV is required (called "aQGC region", aQGC represents anomalous quartic gauge coupling) to improve sensitivity to aQGC signal.

In neutrino channel, at least 1 photon and 2 jets are required. As a neutrino pair from Z boson decay, missing $E_{\mathrm{T}}(E_{\mathrm{T}}^{miss}) > 100$ GeV are required. Avoiding pseudo E_{T}^{miss} arise from mismeasurement of objects, separation between E_{T}^{miss} and jet/γ in transverse plane is required as $\Delta\phi(\vec{p}_{\mathrm{T}}^{miss}, \gamma jj) > 3\pi/4,\ \ \Delta\phi(\vec{p}_{\mathrm{T}}^{miss}, \gamma) > \pi/2,\ \ \Delta\phi(\vec{p}_{\mathrm{T}}^{miss}, j) > 1$.

Additionally, to enhance aQGC search sensitivity, following cuts are required.

$$\Delta\eta_{jj} \quad = \quad |\eta_{j1} - \eta_{j2}| > 2.5$$

$$
\begin{aligned}
\xi_\gamma &> 0.3 \\
&\text{where } \xi = \left|\frac{\eta - \overline{\eta}_{jj}}{\Delta\eta_{jj}}\right| \text{ with } \overline{\eta}_{\rm jj} = \frac{\eta_{\rm j1}+\eta_{\rm j2}}{2},\ \Delta\eta_{\rm jj} = \eta_{\rm j1}-\eta_{\rm j2} \\
p_{\rm T}^{\rm balance} &> 0.1 \\
&\text{where } p_{\rm T}^{\rm balance} = \frac{|\vec{p}_{\rm T}^{\,miss} + \vec{p}_{\rm T}^{\,\gamma} + \vec{p}_{\rm T}^{\,j_1} + \vec{p}_{\rm T}^{\,j_2}|}{E_{\rm T}^{miss} + |\vec{p}_{\rm T}^{\,\gamma}| + |\vec{p}_{\rm T}^{\,j_1}| + |\vec{p}_{\rm T}^{\,j_2}|} \\
m_{jj} &> 600 \text{ GeV}
\end{aligned}
$$

2.2 Background estimation

In charged lepton channel, dominant background are Z +jets which is misidentified hadronic jets as photons (fake photons). Due to MC doesn't describe fake photon well, ABCD method are used, detail is described in [6]. In a nutshell, events passed all requirements without photon isolation and/or identification criteria are defined B or C (D if fails both) which are dominated fake photon. Then fake photon events in signal region is given by A=B×C/D. The other backgrounds are estimated by MC. Summary of events yields are shown in table 1.

Table 1: Summary of events observed in data and estimated composition for charged lepton channel. The Z +jets contribution in this table is taken as a fixed fraction, $(23 \pm 6)\%$. The last line corresponds to the sum of the two previous lines ($N_{Z\gamma\rm QCD} + N_{Z\gamma\rm EWK}$). The uncertainties correspond to the statistical and systematic uncertainties added in quadrature [5].

	Inclusive region $Z(\ell^+\ell^-)\gamma + \geq 2$ jets		Control region $150 < m_{jj} < 500$ GeV		Search region $m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	781	949	362	421	58	72
Z+jets bkg.	134 ± 36	154 ± 42	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	88 ± 17	91 ± 18	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{\rm data} - N_{\rm bkg}$	559 ± 46	704 ± 53	258 ± 24	308 ± 27	44 ± 7	58 ± 8
$N_{Z\gamma\,\rm QCD}$ (Sherpa MC)	583 ± 41	671 ± 47	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\,\rm EWK}$ (Sherpa MC)	25.4 ± 1.5	27.3 ± 1.7	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7
$N_{Z\gamma}$ (Sherpa MC)	608 ± 42	698 ± 49	258 ± 25	299 ± 27	48 ± 6	53 ± 6

In neutrino channel, dominant background is $W(l\nu)\gamma$+jets events which is estimated by MC and normalization is corrected at control region. Second largest source of background is $Z(\nu\nu)$+jets background which is estimated by same as charged lepton channel.

2.3 Results

Figure 1 shows $\xi_{Z\gamma}$ distribution in search region for charged lepton channel and $E_{\rm T}^{\gamma}$ distribution in neutrino channel. Fiducial cross section extraction of $Z\gamma jj$ EWK or EWK+QCD productions are performed by profile likelihood ratio test statistic at charged lepton channel. Neutrino channel is not used because of it has limited number of signal events expected, but used in aQGC search. Definition of fiducial region is described in [5]. Best-fit value of signal strength is found to be

$$\sigma_{Z\gamma jj}^{\rm EWK} = 1.1 \pm 0.5(\text{stat}) \pm 0.4(\text{stst}) \text{ fb} = 1.1 \pm 0.6 \text{ fb} \tag{2.1}$$

The statistical uncertainty on $\sigma_{Z\gamma jj}$ is 40%, while systematic uncertainty is 38% which dominated by 36% of jet energy scale. And MC prediction by VBFNLO[7] is

$$\sigma^{\text{VBFNLO,EWK}}_{Z\gamma jj} = 0.94 \pm 0.09 \text{ fb} \tag{2.2}$$

compatible with this measurement. The significance of the observed EWK production is 2.0σ (1.8σ expected), upper limit on cross-section is 2.2 fb with 95% C.L. of CL_S techniques [8].

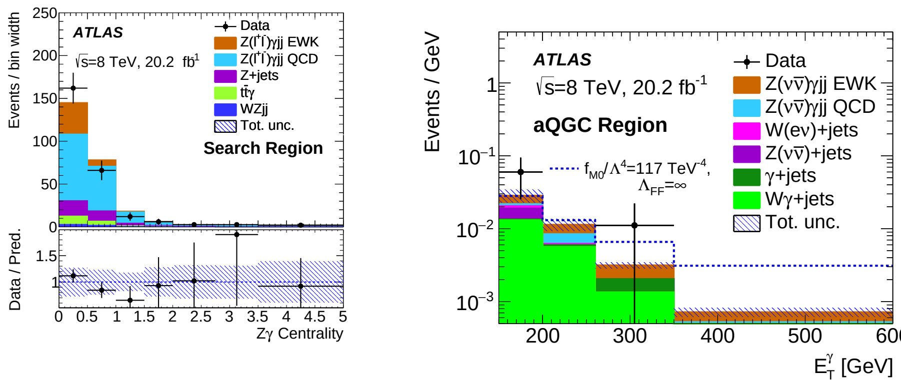

Figure 1: $Z\gamma$ Centrality ($\xi_{Z\gamma}$) in search region for charged lepton channel (left), E_{T}^{γ} in neutrino channel (right) [5].

3. Triboson in $WW\gamma/WZ\gamma$ final state

As long as VBS, triboson final state provides rich information of QGC. While $WW\gamma$ processes have been found at LEP already, measurement at LHC probes higher energy interaction than results obtained from LEP which have much more sensitivity to aQGC. Final states studied in this analysis are opposite-sign full leptonic($e\nu\mu\nu\gamma$) and semileptonic ($l\nu qq\gamma$) final states.

3.1 Event selection

In full leptonic channel, opposite-sign e/μ pair and at least one photon are required. Events which have 3rd lepton and any jets are vetoed. Considering two neutrino from W boson decay, $E_{\text{T}}^{miss} > 15$ GeV are required. Avoiding Drell-Yan process which have τs are suppressed by $m_{e\mu} > 50$ GeV. In semileptonic channel, 1 e or μ, at least 2 jets with $70 < m_{jj} < 100$ GeV and at least one photon are required. Events which have 2nd lepton are vetoed. $E_{\text{T}}^{miss} > 30$ GeV and $m_T > 30$ GeV are required as leptonically decaying W boson.

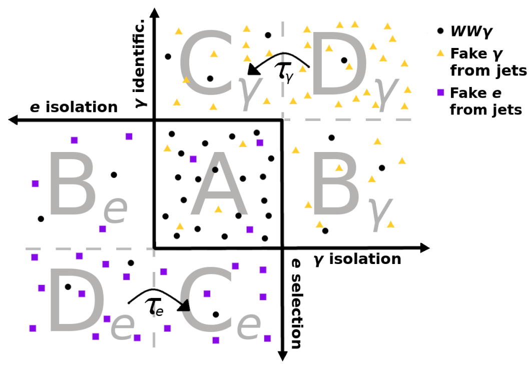

Figure 2: Schematic drawing of the combination of the two two ABCD method to estimate the background from events containing fake γ (triangles) and fake e (squares) from jets. The factors τ_γ and τ_e are transfer factor from D to C region, those are extracted simultaneous fit [9].

3.2 Background estimation

In full leptonic channel, dominant backgrounds are $t\bar{t}\gamma, Z\gamma, WZ\gamma$, which estimated by MC. But fake

γ cannot be negligible. In this analysis, two ABCD method are performed simultaneously to extract both e and γ fakes, schematic drawing are shown in figure 2. In semileptonic channel, dominant backgrounds are W +jets and fake γ/lepton, those scale are estimated by simultaneous fit with control region which inverse of mass window cut of dijets system ($70 < m_{jj} < 100$ GeV). Figure 3 shows m_{jj} distribution.

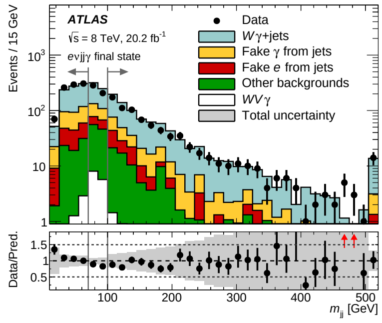

Figure 3: m_{jj} distribution for semileptonic channel [9].

3.3 Results

Figure 4 shows E_{T}^{γ} distribution for both full leptonic and semileptonic channel. Sensitivity is not enough to measure cross section of signal, upper limits are set as shown in table 2.

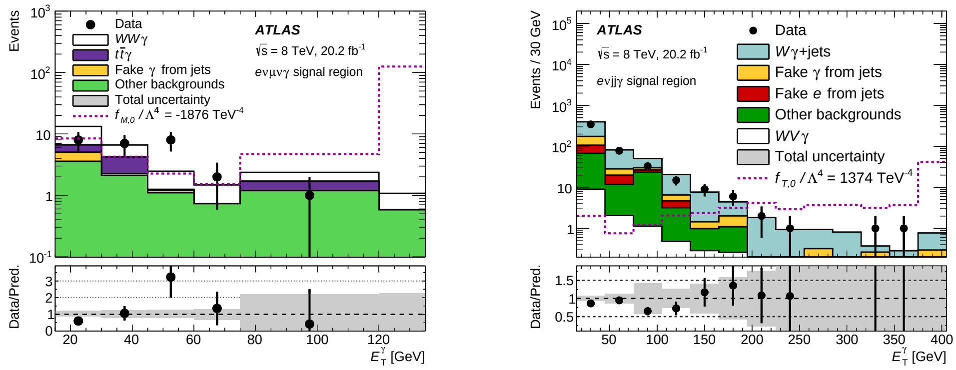

Figure 4: E_{T}^{γ} distribution at full leptonic signal region (left), semileptonic signal region (right) [9].

Table 2: Summary of upper limit on standard model triboson processes for each full leptonic and semileptonic final states [9].

		E_{T}^{γ} threshold [GeV]	Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	120	0.3	$0.3^{+0.3}_{-0.1}$	0.076
Semileptonic	$e\nu jj\gamma$	200	1.3	$1.3^{+0.5}_{-0.3}$	0.057
	$\mu\nu jj\gamma$	200	1.1	$1.1^{+0.5}_{-0.3}$	0.051
	$\ell\nu jj\gamma$	200	0.9	$0.9^{+0.3}_{-0.2}$	0.054

4. limits on aQGC

Both analysis are using Effective Field Theory (EFT) approach [10], effective lagrangian is given by,

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} O_n \tag{4.1}$$

where $\mathscr{L}_{SM}$ is standard model lagrangian, f_n is coefficients, Λ is cut-off scale, O_n is operator, detail is described in [11].

Limits on each coefficient is summarized at table 3 and figure 5.

	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n=0$	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
$n=2$	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8

Table 3: Summary of limit on EFT coefficients in $Z\gamma jj$ analysis [5].

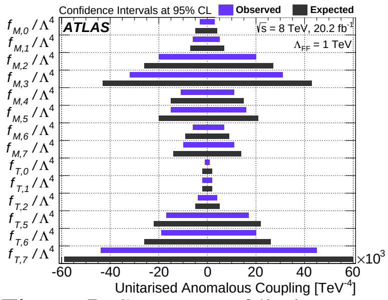

Figure 5: Summary of limit on EFT coefficients in $WV\gamma$ analysis [9].

5. Summary

Study for VBS in $Z\gamma jj$ final state and triboson in $WV\gamma$ final state with the ATLAS detector at the LHC are performed. Both analyses limited by statistics but those have good sensitivity to standard processes and already set limits on aQGC.

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