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Measurement of $W\gamma$ and $Z\gamma$ production cross sections in pp collisions at $7\ TeV$ and limits on anomalous triple gauge couplings with the ATLAS detector

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This paper presents measurements of $W\gamma$ and $Z\gamma$ production in 1.02 fb^{-1} of 7 TeV pp collision data recorded with the ATLAS detector at the LHC. The W and Z bosons are detected through their decay to electrons and muons. Cross sections and kinematic distributions are measured and compared to Standard Model expectations. No evidence for physics beyond the Standard Model is observed and limits on anomalous $WW\gamma$ and $ZZ\gamma/Z\gamma\gamma$ couplings are presented.

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Measurements of $W\gamma$ and $Z\gamma$ di-boson production at collider experiments provide direct tests on the electroweak non-Abelian $SU(2)_L \times U(1)_Y$ gauge theory of the Standard Model (SM). The cross sections are sensitive to the couplings at the triple gauge boson vertex. An excess of high transverse energy photons compared to SM expectations would imply new physics and can be interpreted as anomalous triple gauge boson couplings (aTGC); either a deviation from the SM predicted $WW\gamma$ couplings $\Delta\kappa_\gamma = \kappa_\gamma - 1$, or SM-forbidden new interactions as λ_γ for $WW\gamma$ and h_3^V and h_4^V for $ZV\gamma$ ($V = \gamma$ or Z) couplings. In this paper, we present measurements of $W\gamma$ and $Z\gamma$ production, via W and Z boson leptonic decay $l^\pm\nu\gamma$ and $l^+l^-\gamma$ ($l = e,\mu$) channels, in pp collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV at the Large Hadron Collider (LHC) [1].

The production cross sections are measured using $1.02 fb^{-1}$ of data collected by the ATLAS experiment. The ATLAS detector is described in detail elsewhere [2]. Events are selected by requiring electrons or muons with high transverse momentum $p_{\mathrm{T}}^{\mathrm{l}} > 25$ GeV within the detector fiducial coverage. Electron candidates must pass calorimeter-based electromagnetic (EM) shower identification cuts and an isolation requirement as $E_{\mathrm{T}}^{\mathrm{iso}} < 6$ GeV, where $E_{\mathrm{T}}^{\mathrm{iso}}$ is the total transverse energy recorded in the calorimeter within a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the electron direction (where ϕ is the azimuthal angle, and η is the pseudo-rapidity defined in terms of the polar angle θ as $\eta = -\ln\ \tan(\theta/2)$), excluding the energy of the electron cluster. Muon candidates are required to pass the isolation requirement as $R^{\mathrm{iso}}(\mu) < 0.1$, where $R^{\mathrm{iso}}(\mu)$ is the sum of the track p_T in a $\Delta R = 0.2$ cone around the muon direction divided by the muon p_T. Photon candidates must have $E_{\mathrm{T}}^{\gamma} > 15$ GeV. They should deposit most of their energy in the EM calorimeter and must pass tight calorimeter shower shape and isolation requirements similar to those for electrons. To suppress the final state radiation (FSR) photon contribution in W or Z charged lepton decay, a requirement on photon-lepton separation $\Delta R(l,\gamma) > 0.7$ is applied. For $W\gamma$ events, the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$ [3] is required to pass the selection $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and the transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system, $M_{\mathrm{T}}(l,\nu) = \sqrt{2p_{\mathrm{T}}^{\mathrm{l}} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos\Delta\phi)}$, must pass $M_{\mathrm{T}}(l,\nu) > 40$ GeV, where $\Delta\phi$ is the azimuthal separation between the directions of the lepton and the missing transverse momentum vector. For $Z\gamma$ candidates, the two leptons must be oppositely charged and have an invariant mass $m(ll) > 40$GeV. For a better comparison to SM predictions, the production processes are categorized into different photon transverse energies, $E_{\mathrm{T}}^{\gamma} > 15, 50$ and 100 GeV, and are analyzed both inclusively with no requirement on the recoil system and exclusively by requiring that there is no hard jet in $W\gamma$ and $Z\gamma$ events, where jets are required to deposit $p_{\mathrm{T}} > 30$ GeV in the calorimeter and to be well separated from the lepton and photon candidates, $\Delta R(l/\gamma, jet) > 0.6$.

Monte Carlo (MC) samples, including full simulation of the ATLAS detector, are used to compare the data to the SM signal and background expectations. The associated photon in $W\gamma$ and $Z\gamma$ events can be produced by radiation from initial state partons (ISR), by final state radiation (FSR) from charged leptons in W or Z decay, by parton-to-photon fragmentation in hard scattering processes or directly through the $WW\gamma$ interaction. Leading-order (LO) matrix element Monte Carlo (MC) generators, ALPGEN [4] and SHERPA [5], are used to model $pp \to l^\pm\nu\gamma$ and $pp \to l^+l^-\gamma$ respectively. The dominant background in selected data comes from V+jets (V=W or Z) QCD contamination, where jets pass the photon selection criteria and are mis-identified as photon candidates. Since these jet-faking photon processes are not well modeled by the MC simulation, V+jets

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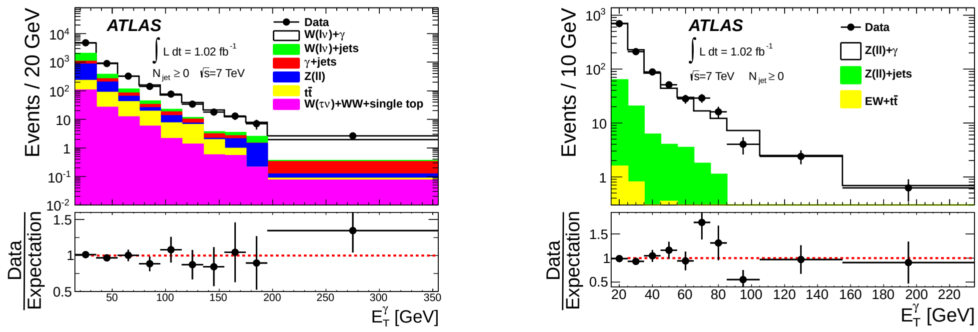

Figure 1: E_T^γ distributions in $W\gamma$ and $Z\gamma$ candidate events [1], with no requirements on the recoil system. The distributions of the expected signals are taken from signal MC simulation and normalized to the extracted number of signal events. The ratio between the numbers of observed data and the expected numbers of the sum of the signal and background is also shown.

backgrounds are estimated from data. A jet-faking photon "pass-to-fail" ratio f_γ is defined as the ratio of "low quality" photon candidates passing or failing the photon isolation requirement. The ratio f_γ is measured in $W(l\nu)/Z(ll)$ inclusive events with photon candidates, which are defined as "low quality" by failing the photon shower-shape requirements but passing background-enriching subsets of these requirements. The estimation of the V+jets background contribution is then obtained by multiplying the measured f_γ by the number of events passing all $V+\gamma$ selections, except the photon isolation requirement. For $W\gamma$ events, another QCD background is γ+jets, where jets or leptons in heavy quark decays are mis-identified as lepton candidates and large apparent $E_{\mathrm{T}}^{\mathrm{miss}}$ arises from the mis-measurement of the jet energies. Similar to the V+jets estimation, a jet-faking lepton "pass-to-fail" ratio f_l is defined with respect to lepton isolation criteria, measured in a QCD-enriching control sample, which requires the events to pass all the $W\gamma$ selection criteria except the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement, and applied to the number of events passing all $W\gamma$ selection criteria except the lepton isolation requirement. Other electroweak backgrounds, such as $W\to\tau\nu$, WW and single top processes, and $t\bar{t}$ production are estimated from full MC simulation. The selected $W\gamma$ and $Z\gamma$ data are compared to the sum of the SM signal predictions and the background estimations, with electron and muon channels combined to reduce the statistical uncertainty. The distributions of E_{T}^{γ} for $W\gamma$ and $Z\gamma$ candidate events are shown in Figure 1 [1].

The measurements of cross sections, in an extended fiducial region as defined in Table 1, for the processes $pp\to l\nu\gamma$ and $pp\to l^+l^-\gamma$ can be expressed as

$$\sigma^{\mathrm{ext}}_{pp\to l\nu\gamma(l^+l^-\gamma)} = \frac{N^{\mathrm{sig}}_{W\gamma(Z\gamma)}}{A_{W\gamma(Z\gamma)}\cdot C_{W\gamma(Z\gamma)}\cdot L}$$

where $N^{\mathrm{sig}}_{W\gamma(Z\gamma)}$ denote the numbers of background-subtracted signal events, L is the integrated luminosity, $C_{W\gamma(Z\gamma)}$ denote the signal selection efficiencies with corrections to account for small discrepancies between data and simulation, and $A_{W\gamma(Z\gamma)}$ are the extended fiducial and kinematic acceptances as given in Table 1. The systematic uncertainties are dominated by the photon identification efficiency and the jet energy scale. The measured cross sections are compared with

Cuts	$pp \to l\nu\gamma$	$pp \to l^+l^-\gamma$
Lepton	$p_T^l > 25$ GeV	$p_T^l > 25$ GeV
	$p_T^\nu > 25$ GeV	
	$\|\eta^l\| < 2.47$	$\|\eta^l\| < 2.47$
Boson		$m_{l^+l^-} > 40$ GeV
Photon	Low : $E_T^\gamma > 15$ GeV	
	Medium : $E_T^\gamma > 60$ GeV	
	High : $E_T^\gamma > 100$ GeV	
	$\|\eta^\gamma\| < 2.37, \Delta R(l,\gamma) > 0.7$	
	isolation fraction $\epsilon_h^p < 0.5$	
Jet	$E_T^{\rm jet} > 30$GeV, $\|\eta^{\rm jet}\| < 4.4$	
	$\Delta R(e/\mu/\gamma, jet) > 0.6$	
	Inclusive: $N^{\rm jet} \geq 0$,	
	Exclusive: $N^{\rm jet} = 0$.	

Table 1: Definition of the extended fiducial regions. p_T^ν is the transverse momentum of the neutrino from W decay, and ϵ_h^p is defined at particle level as the ratio between the sum of the energies carried by final state particles in a cone $\Delta R < 0.4$ around the photon direction and the energy carried by the photon.

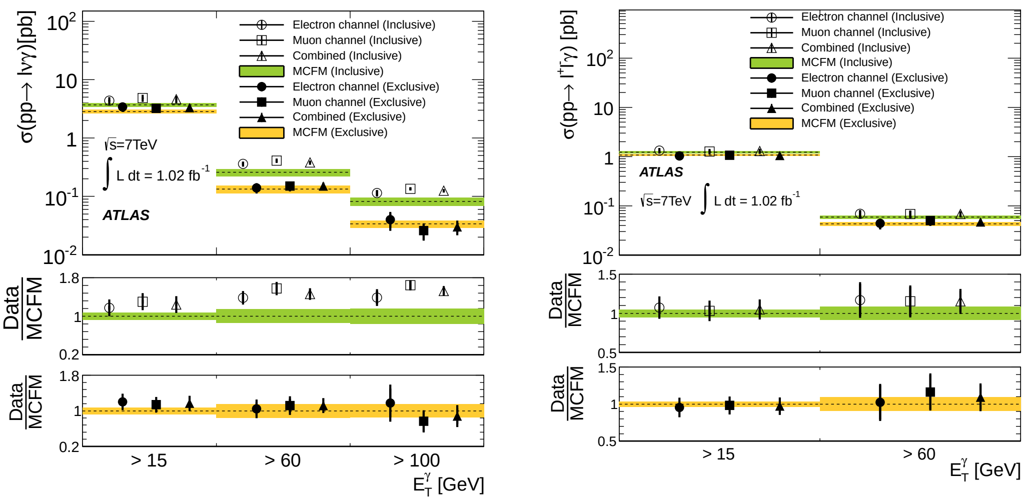

Figure 2: The measured cross sections of $W\gamma$ and $Z\gamma$ production as functions of the photon E_T^γ threshold [1], together with the SM model predictions.

theoretical predictions up to next-to-leading order (NLO), derived from the MCFM [6] program, in the extended acceptance region. Figure 2 [1] shows all the cross section measurements for $W\gamma$ and $Z\gamma$ production and the comparisons to particle-level SM expectations, at different photon E_T^γ thresholds and inclusive or exclusive jet activity. There is good agreement between the measured cross sections for the exclusive events and the MCFM prediction. For inclusive production, the MCFM NLO prediction includes real parton emission processes only up to one radiated quark or gluon. The lack of higher order QCD contributions results in an underestimation of the predicted

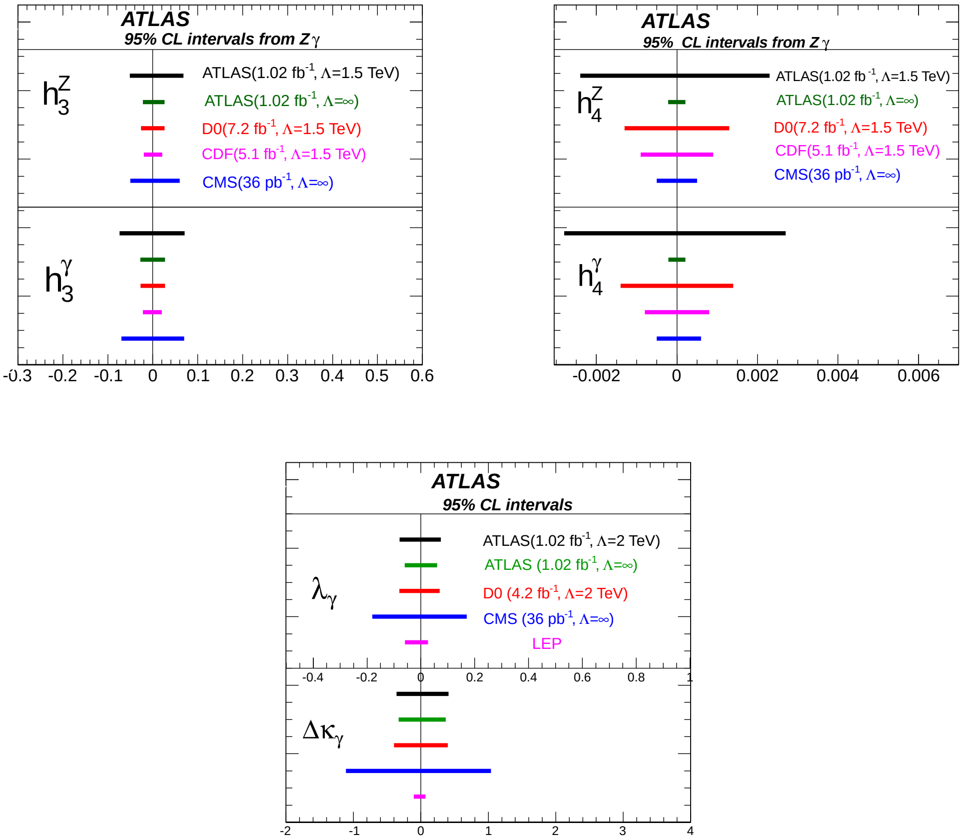

Figure 3: The 95% CL intervals for anomalous couplings of h_3^V, h_4^V and $\Delta\kappa_\gamma$ and λ_γ [1].

cross sections, especially for events with high $E_{\rm T}^{\gamma}$ photons, which have significant contributions from multi-jet final states in the $W\gamma$ processes.

Measurements of the exclusive extended fiducial cross sections for $W\gamma$ production with $E_{\rm T}^{\gamma} > 100\ GeV$ and $Z\gamma$ production with $E_{\rm T}^{\gamma} > 60\ GeV$ are used to extract aTGC limits. The cross section predictions with aTGCs ($\sigma_{W\gamma}^{\rm aTGC}$ and $\sigma_{Z\gamma}^{\rm aTGC}$) are obtained from the MCFM generator. A new physics energy scale Λ is introduced to avoid unitarity violation at very high energy. The limits on a given aTGC parameter (e.g. h_i^V) are extracted from the Bayesian posterior, given the extended fiducial measurements. The Bayesian probability density function is obtained by integrating over the nuisance parameters corresponding to all systematic uncertainties and assuming a flat Bayesian prior in aTGC parameters. The results are shown in Figure 3 [1] at 95% C.L. and compared with the LEP[7], Tevatron[8][9] and CMS[10] measurements.

In summary, we present measurements of $W(l\nu)\gamma$ and $Z(ll)\gamma$ cross sections in pp collisions at $\sqrt{s} = 7\ TeV$. The analysis uses 1.02 fb^{-1} data accumulated at ATLAS experiment. The results are compared to SM predictions up to NLO. The SM predictions for the exclusive $W\gamma$ and $Z\gamma$ production agree well with the data, while the measured inclusive $W\gamma$ cross sections are larger than the NLO calculations in the high photon transverse energy region. The deviation of inclusive measurements from SM expectation implies the necessity of including higher order corrections beyond NLO. Limits on anomalous triple gauge couplings ($\Delta\kappa_\gamma$,λ_γ,h_3^V and h_4^V) are derived from the photon E_T^γ distributions of exclusive measurements. The limits obtained are compatible with those from LEP and Tevatron and are more stringent than previous LHC results.

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