Standard Models Tests and Searches with Photons at the LHC

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We report on the sensitivity of the LHC experiments to the Standard Model predictions for $W\gamma$ and $Z\gamma$ productions in pp collisions with final states containing electrons, muons and photons. The studies use detector simulation data at $\sqrt{s} = 14$ TeV including calibration and alignment corrections. The results show that the cross-section measurements of $W\gamma$, and $Z\gamma$ can be established with significance better than 5 sigma for the first 0.1 fb^{-1} of integrated luminosity. The sensitivities to anomalous triple gauge boson couplings is also estimated. The measurements can be significantly improved with 1 fb^{-1} of data over the results from the Tevatron.

1 Introduction

The Large Hadron Collider (LHC) is built for finding possible evidence of the Higgs boson and new physics beyond the Standard Model. Two general purpose experiments, ATLAS [1] and CMS [2], have been constructed to study proton-proton collisions at a center of mass energy of 14 TeV. Measurements of electroweak interactions shall be accurate and the data samples will be used as reference for calibration of detector response of leptons, photons and jets. Detection of photons in the final states is important for many analyses such as the searches for Higgs bosons, supersymmetry, and precision measurements of Standard Model processes. The diboson production of $W\gamma$ and $Z\gamma$ probes triple gauge boson couplings (TGC) of $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ vertices, and therefore the non-Abelian structure of the Standard Model [3]. Charged TGCs of $WW\gamma$ and WWZ are predicted, while those involving only neutral gauge bosons (Z, γ) are absent at tree-level, and the higher order corrections are at the 10^{-4} level [4]. If there will be contributions of anomalous couplings, the signature would be obtained for enhanced production cross-sections particularly at high transverse momentum of the bosons. Indication of new physics is explored by measuring deviations of these distributions to theoretical predictions.

In this report we first discuss measurements of W and Z bosons in leptonic decays to electrons and muons. Detection of W and Z associated with a photon is studied with Monte Carlo samples applying full detector layout for realistic understanding of the event selection. The sensitivities to anomalous triple gauge couplings are determined.

2 Leptonic W and Z decays

The LHC provides a new energy domain for exploration beyond LEP and Tevatron. The measurements described here will be dominated by uncertainties in the electroweak sector of the Standard Model. Study of leptonic decays of W and Z bosons will be the first to be exploited. These processes have large production cross sections and the theoretical understanding is very advanced to next-to-leading order (NLO). Their experimental signatures are very clean, in particular for $Z \to ll$, and will be extensively used for detector calibration and tuning of Monte Carlo simulation.

Events of $Z \to e^+e^-$ and $\mu^+\mu^-$ are triggered by high p_T leptons. The typical event selection requires finding a pair of oppositely charged leptons above a p_T threshold in a mass interval adjacent to the Z mass in the fiducial volume of the detector (typically $|\eta| < 2.5$, limited by the tracking detectors). The invariant mass spectra of the CMS study [5] for $Z \to e^+e^-$, expected for 10 pb^{-1}, is plotted in Figure 1. $W^\pm \to e^\pm\nu$ or $\mu^\pm\nu$ events are selected similarly with a single lepton trigger, finding an isolated high p_T lepton with large missing energy, and the transverse mass consistent with the W. The transverse mass distribution of the ATLAS analysis [6] is shown in Figure 1 for $W^\pm \to \mu^\pm\nu$ expected for an integrated luminosity of 50 pb^{-1}. The large statistics of signal events suggest that the cross section measurements will be dominated by systematic errors. An overall uncertainty of about 5% can be achieved with 50 pb^{-1} in the W channels, mainly due to background uncertainty. The precision for Z channels is expected for 3% with the uncertainty coming from the lepton selection [6]. These values will be reduced with more stringent selections when the available data statistics increases. The theoretical uncertainty from modeling the parton density functions (PDF) has the effect on absolute normalization, and is estimated to be $6-7\%$ [7]. The uncertainty on luminosity, typically obtained by measuring forward elastic scattering, is estimated to be 10% at the beginning

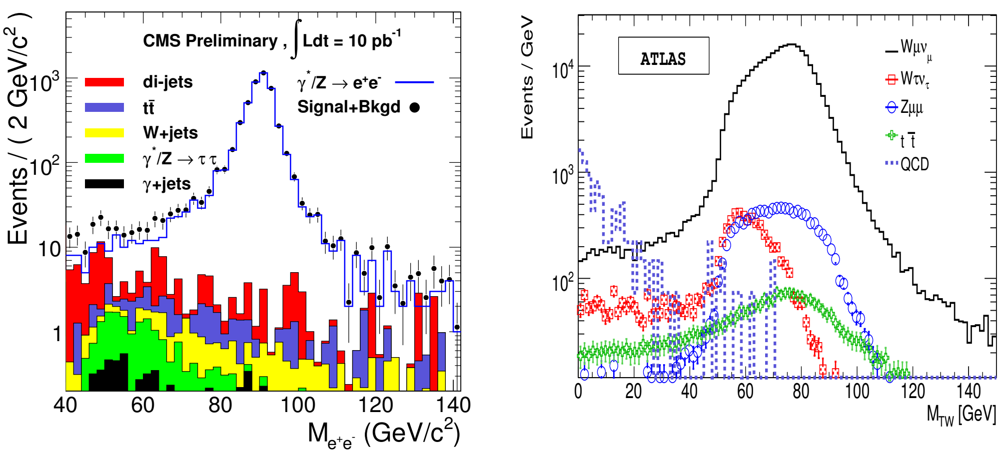

Figure 1: Left: Invariant mass distribution in the $Z \to \mu\mu$ channel as expected in CMS for an integrated luminosity of 10 pb^{-1} [5]. Right: Transverse mass distribution in the $W \to \mu\nu$ events channel as expected in ATLAS for an integrated luminosity of 50 pb^{-1} [6].

of data taking.

3 W and Z production associated with a photon

Both ATLAS and CMS collaborations have carried out studies on diboson events with leptons and photons in the final states for the production cross sections and the sensitivity to anomalous triple gauge boson couplings. The tree-level Feynman diagrams for production of a W or a Z boson accompanied with a photon are shown in Figure 2. The diagrams of $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ coupling vertices are also illustrated. At LHC the energy will be seven times higher than at the Tevatron, the LHC sensitivity to anomalous couplings is expected to be improved by orders of magnitude. Comparison of the production cross-sections are listed in Table 1.

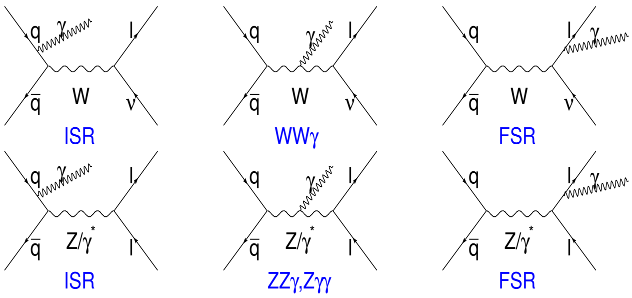

Figure 2: The Standard Model tree-level diagrams for $W\gamma$ and $Z\gamma$ productions at hadron colliders.

Selections for $W\gamma$ and $Z\gamma$ events have profited from the clean signals of the leptonic final states and by the well established identification of W and Z bosons. The $W\gamma$ candidates are inclusive $e^{\pm}\gamma$ and $\mu^{\pm}\gamma$ events having one electron or muon observed with the absence of the oppositely charged lepton of the same flavor. The neutrino from W decay escapes detection and introduces a large transverse energy imbalance. Signal events of interest are those with a photon of initial state radiation (ISR) or of the $WW\gamma$ coupling. The $WW\gamma$ coupling introduces a destructive interference with the ISR diagram, and leads to cancellation of $W\gamma$ production with *zero amplitude* at $\cos\theta_{\bar{q},\gamma} = \pm 1/3$, where $\theta_{\bar{q},\gamma}$ is the photon scattering angle to the incoming anti-quarks.

Mode	$\sqrt{s} = 1.96$ TeV	$\sqrt{s} = 14$ TeV
$W^{\pm}\gamma$	19.3	451
$Z\gamma$	4.74	219

Table 1: The Standard Model total cross-sections (pb) calculated to NLO [8] for $W\gamma$ and $Z\gamma$ with $E_T^{\gamma} > 7$ GeV and $\Delta R(\ell,\gamma) > 0.7$.

Events with a photon of final state radiation (FSR) are considered as background. A FSR photon can be distinguished by its low p_T and small angle to the lepton from which it is radiated, and in addition, by the invariant masses of the photon with observable particles. Illustrated in Figure 3 (left) are the transverse mass distributions of the CMS study [9] for signal events with a ISR (or $WW\gamma$) photon and background of radiative W decays with a FSR photon. The radiative W decays are distinguishable for having transverse mass distributed around the W boson mass. Contribution of anomalous TGC are searched for events with a high transverse mass or a high p_T photon, in which the background is dominated by inclusive $W + jets$ events with jet remnants like π^0 faking photons. Fake photons are suppressed by requiring isolation and subdetector measurements of the photon shower profiles.

Selection of $W\gamma$ events has been studied with a cut-based method by CMS and a Boosted

Decision Tree (BDT) algorithm [10] by ATLAS. The event triggers are evaluated with realistic detector simulations. The BDT selection requires a low $p_T(\gamma)$ threshold of 10 GeV to optimize event yield for early LHC running. The expectations for 1 fb^{-1} of data, at 65% signal efficiency, are 1604 (2166) events for the electron (muon) channels, and the corresponding background are 1180 (1340) events, respectively [6].

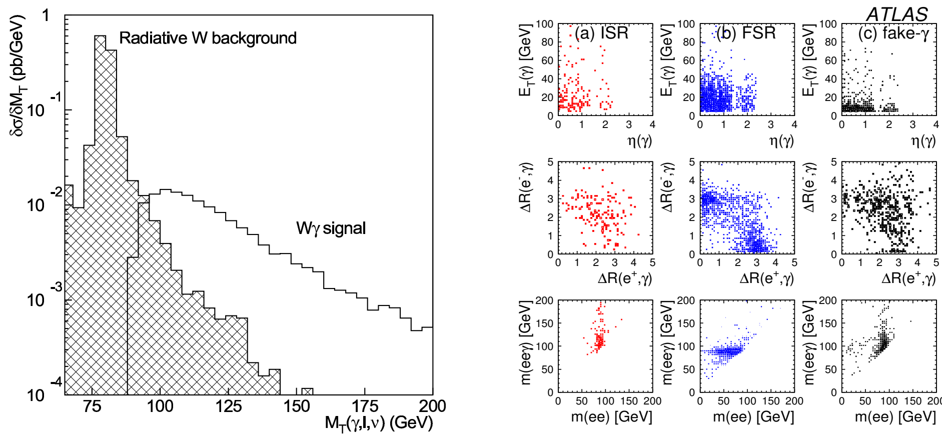

Figure 3: Left: Transverse mass $M_T(l, \nu, \gamma)$ of $W\gamma$ events with a ISR (or $WW\gamma$) photon or of radiative W decays with a FSR photon (hatched) [9]. Right: Distributions of $Z(ee)\gamma$ event variables for signal with an ISR photon, and backgrounds with a FSR or a fake photon [6].

The $Z\gamma$ candidates are selected for inclusive $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events with an ISR photon. The Monte Carlo used does not include $ZZ\gamma$ nor $Z\gamma\gamma$ vertices as neutral TGCs are forbidden at tree-level. The Z boson is reconstructed using the pair of most energetic leptons of the same flavor with opposite charges. Sources of background are inclusive Z production with a FSR photon radiated by a Z decay lepton ($Z \to l^+l^-\gamma$); and inclusive $Z + jets$ with a fake photon reconstructed.

Distributions of $Z\gamma$ signal and background events are shown in Figure 3 (right) for some of the event variables. The invariant mass distributions of the lepton-pair and photon are distinguishable for radiative Z decays with $m(l^+l^-\gamma)$ consists with the Z mass. The opening angles of the photon to leptons provide additional selection for FSR photons. Events with fake photons resemble the signal in the invariant mass and angular distributions. The ATLAS study has conducted a BDT algorithm to optimize $Z\gamma$ selection from background with a fake photon. The expected number of events for 1 fb^{-1} of data, at 67% signal efficiency, are 367 (751) events for electron (muon) channels with 187 (429) background events, respectively.

Unlike the $W\gamma$ measurement which suffers under the undetected neutrino, all observables in the $Z\gamma$ measurement are fully determined, and the cross section measurement is thus complementary to $W\gamma$ for the contribution of $WW\gamma$ coupling. $W\gamma$ and $Z\gamma$ are two of the diboson processes having large production cross sections. With the initial LHC running of an integrated luminosity of 0.1 fb^{-1}, hundreds of selected events are expected and the detection significance will be greater than 10 σ.

4 Sensitivity to anomalous couplings

A signature for anomalous triple gauge boson couplings is an increased cross-section with respect to the Standard Model prediction, especially at high vector boson p_T. The effective Lagrangian for TGCs is formulated assuming Lorentz and electromagnetic gauge invariance. The $WW\gamma$ coupling that attributes to $W\gamma$ production is parameterized with two parameters, κ_γ and λ_γ, and the Standard Model values are $\Delta\kappa_\gamma \equiv \kappa_\gamma - 1 = 0$, and $\lambda_\gamma = 0$ [11]. The neutral $ZZ\gamma$ and $Z\gamma\gamma$ couplings in $Z\gamma$ production are parameterized with eight parameters, h_{i0}^V ($i = 1...4$, and $V = Z, \gamma$). CP invariance and parity conservation forbids h_{10}^V and h_{20}^V, and the Standard Model values at tree-level are all zero.

With anomalous coupling, the diboson production amplitudes grow with energy. This is avoided by scaling the TGC parameters with a form factor, e.g. $\Delta\kappa(\hat{s}) = \Delta\kappa/(1+\hat{s}/\Lambda^2)^n$ [12], where $\sqrt{\hat{s}}$ is the invariant mass of the vector-boson pair and $\Delta\kappa(0)$ is the coupling value in the low energy limit. The cutoff parameter, Λ, is the mass scale where the new phenomenon responsible for the anomalous couplings would be directly observable. The value is chosen such that the extracted limit from data for a certain diboson production process is less than the unitarity limit. With 0.1-1.0 fb^{-1} of integrated luminosity at early LHC running, Λ values of 2-3 TeV are used.

The photon transverse energy in $W\gamma$ and $Z\gamma$ productions is the most sensitive variable to anomalous couplings and is directly measurable. The sensitivity to anomalous TGCs is obtained by comparing the measured production cross-section and the photon $p_T(\gamma)$ distribution to models with anomalous TGCs. The Monte Carlo generator of Baur *et al.* [8] is used to compute differential cross sections over a grid of points in the parameter space. Distributions of the fully simulated Standard Model events are re-weighted by the generator calculations of $d\sigma(TGC)/d\sigma_{SM}$. A binned likelihood fitting procedure on the photon transverse energy $E_{\rm T}(\gamma)$ spectra is followed to extract the 95% C.L. intervals of TGC parameters. The production of $W\gamma$ events involves exclusively the $WW\gamma$ triple gauge coupling. The one and two-dimensional limits extracted for $\Delta\kappa_\gamma$ and λ_γ are shown in Figure 4 for $p_T(\gamma)$ distribution of the ATLAS

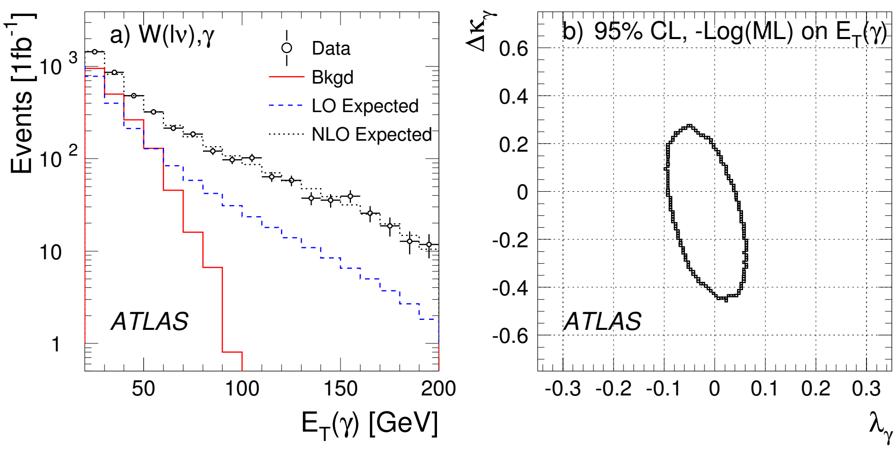

Figure 4: The photon transverse energy distributions of $W(l\nu)\gamma$ ($l = e, \mu$) events, and the 95 % confidence contour extracted in the $\Delta\kappa_\gamma$, λ_γ parameter space ($\Lambda = 2$ TeV) for 1 fb^{-1} of data [6].

study [6]. The signal expectations at the tree-level and NLO are plotted as the dashed and dotted lines. The 95% confidence contour obtained is plotted in the $\Delta\kappa_\gamma$, λ_γ parameter space. The sensitivities to λ_γ and $\Delta\kappa_\gamma$ for 1, 10 and 30 fb^{-1} are listed in Table 2.

Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings would enhance the event rates in the large $p_T(\gamma)$ region. This is shown in Figure 5 for the $p_T(\gamma)$ distributions with a non-zero h^Z_{40}, and the dependence on the Λ scale is illustrated for $\Lambda = 2$ and 3 TeV. The sensitivity to anomalous couplings is studied by CMS [13] for two of the CP conserving parameters, h^Z_{30} and h^Z_{40}, with several Λ scales. The binned likelihood fits have been conducted for the $p_T(\gamma)$ distributions normalized to 10 and 100 fb^{-1} of data. The confidence contours of 68%, 90% and 95% with $\Lambda =$ 3 TeV are shown in Figure 5. The one dimensional limits obtained are listed in Table 3.

	1 fb^{-1}	10 fb^{-1}	30 fb^{-1}
$\Delta\kappa_\gamma$	[-0.43, 0.20]	[-0.26, 0.07]	[-0.11,0.05]
λ_γ	[-0.09, 0.04]	[-0.05, 0.02]	[-0.02,0.01]

Table 2: One dimensional limits (95% C.L.) for $WW\gamma$ coupling with $\Lambda = 2$ TeV [6].

Λ (TeV)		10 fb^{-1}	100 fb^{-1}
2	$h^Z_{30}(10^{-3})$	[-5.2, 5.2]	[-2.4, 2.2]
	$h^Z_{40}(10^{-5})$	[-6.4, 6.8]	[-2.9, 3.2]
3	$h^Z_{30}(10^{-3})$	[-2.3, 2.3]	[-1.5, 1.5]
	$h^Z_{40}(10^{-5})$	[-1.9, 1.8]	[-0.97, 0.85]
6	$h^Z_{30}(10^{-3})$	[-1.2, 1.3]	[-0.65, 0.64]
	$h^Z_{40}(10^{-5})$	[-0.42, 0.40]	[-0.18, 0.17]

Table 3: One dimensional limits (95% C.L.) for CP-conserving TGC parameters h^Z_{30} and h^Z_{40} in $Z\gamma$ production [13].

Both ATLAS and CMS have demonstrated significantly higher sensitivities to anomalous TGCs than those reported by the LEP and Tevatron experiments [14, 15]. The confidence intervals for parameters in $W\gamma$ and $Z\gamma$ productions are expected to be improved with 1 fb^{-1} of the early running data.

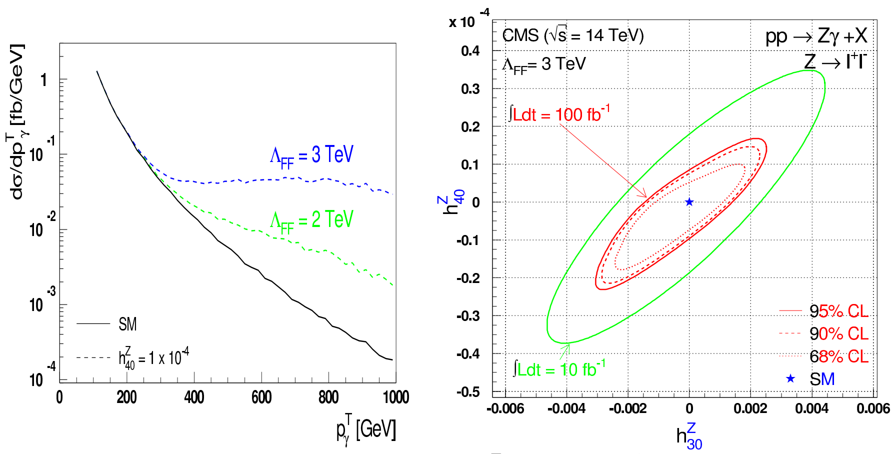

Figure 5: Left: photon p_T of $Z\gamma$ production with $h^Z_{40} = 1 \times 10^{-4}$ and $\Lambda = 2$ and 3 TeV. Right: the sensitivity contours in the h^Z_{30}, h^Z_{40} parameter space obtained with $\Lambda = 3$ TeV for 10 and 100 fb^{-1} of data [13].

5 Summary

Detailed data analyses are being eagerly pursued for the LHC start up. Studies of inclusive W and Z events are among the most urgent for measurements of Standard Model physics in a much extended kinematic region. Diboson events of $W^{\pm}\gamma$ and $Z\gamma$ signals will be established in leptonic channels with the initial statistics of 0.1 fb^{-1}. Measurement of high p_T photons will be sensitive to anomalous coupling which leads to indications of new physics phenomena. Confidence intervals on anomalous couplings are expected to be significantly improved with respect to the present values.

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