Gauge Couplings at the LHC

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The potential for measuring the di-boson production at the LHC has been studied by both ATLAS and CMS experiments, using full detector simulation of the signal and background samples. The studies show that some di-boson signals (i.e. $W\gamma$ and WW) can be observed with as little as $\sim$ 100 pb^{-1} of data. The expected limits on the anomalous triple gauge couplings are also presented in this paper.

1 Introduction

In the standard model (SM), the non-abelian nature of the $\mathrm{SU(2)_L \times U(1)_Y}$ gauge symmetry allows the gauge bosons to interact not only with matter particles but also with themselves. The couplings between three gauge bosons are referred to as Triple Gauge-Boson Couplings (TGC's). In SM, only charged couplings (e.g. WWZ, $WW\gamma$) are allowed. Whereas pure neutral couplings are forbidden (e.g. ZZZ, $Z\gamma\gamma$). However, new physics beyond the SM may introduce anomalous TGCs which could allow neutral couplings, or modify the charged TGC couplings. The anomalous parameters for charged TGC's, in the case that conserve parity and charge conjugation, are λ_γ, λ_Z, $\Delta\kappa_\gamma$, $\Delta\kappa_Z$ and Δg_1^Z [1]. For neutral TGC's, the anomalous parameters are f_4^Z,f_5^Z, f_4^γ and f_5^γ [2]. In the SM at the tree level, these anomalous coupling parameters have values of zero.

At the LHC, the TGC can be studied through the measurements of the di-boson productions (WW, WZ, ZZ, $W\gamma$ and $Z\gamma$). The Feynman diagrams of these productions are shown in Figure 1. The s-channel production gives us a direct probe of the TGC vertex. If anomalous TGC is present, it will enhance the di-boson production rate, particularly at the high transverse momentum of the boson. As di-boson production is also one of the backgrounds to several important searches at the LHC (e.g. searches for Higgs boson, Supersymmetry and New Gauge bosons), thus, it is essential for us to have a good understanding of this production process.

The ATLAS and CMS experiments have performed several simulation studies on their sensitivities to the di-boson production measurements at the center of mass energies of $\sqrt{s} = 10$ TeV and $\sqrt{s} = 14$ TeV [3]. The predicted production cross section at $\sqrt{s} = 14$ TeV varies from $\sim$ 15 pb for ZZ production to $\sim$ 450 pb for $W\gamma$ production. All the studies are performed using the leptonic decays of the W and Z bosons, and cut-based selection method is used to separate the signal from the background. The ATLAS experiment also employs a multivariate algorithm, the Boosted Decision Trees (BDT), to make better use of the event information to discriminate the signal from the background. In the following sections I will summarize the results of the simulation studies from both experiments.

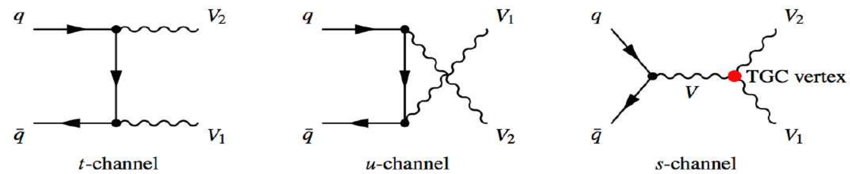

Figure 1: Feynman diagrams of di-boson productions.

2 Measurement of Di-boson Productions

2.1 WW Production

The WW production is studied by the ATLAS and CMS experiments in the $W^+W^- \to l^+\nu l^-\bar{\nu}$ decay channel, where l is either an electron or a muon. This measurement can probe both the $WW\gamma$ and WWZ vertex. The main sources of background are from productions of $t\bar{t}$, W+jets, Drell-Yan and di-boson (WZ, ZZ, $Z/W\gamma$). The signal events are pre-selected by requiring two opposite charged high transverse momentum (p_T) leptons and large missing transverse energy ($\not{E}_T$) due to the undetected neutrinos. Tighter cuts are applied to further reduce the background contributions. These cuts include no reconstructed jet in the event and that the invariant mass of the two same-flavor leptons should not be consistent with the Z boson. Figure 2 shows the di-lepton mass distribution from CMS and the BDT output distribution from ATLAS. Both experiments are expected to observe evidence of the WW signal with as little as 100 pb^{-1} of data. ATLAS' expected sensitivities to the anomalous TGC's from the WW measurement, at 95% confidence level (C.L.), is shown in Table 1.

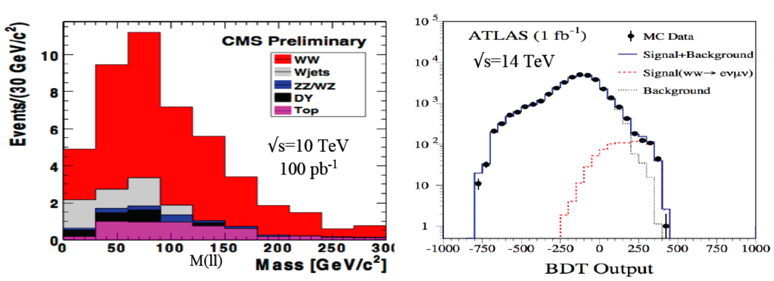

Figure 2: (LEFT) Di-lepton mass distribution from CMS and (RIGHT) BDT output distribution from ATLAS for the WW measurement.

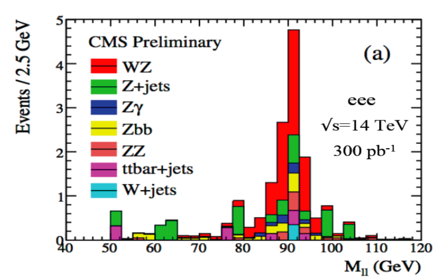

Figure 3: The di-electron mass distribution from CMS in the "*eee*" channel for the WZ measurement.

2.2 WZ Production

To study the WZ production, both experiments consider the channel where W boson decays into a lepton and neutrino, and the Z boson decays into a pair of opposite charged leptons. The signal events are selected by requiring three isolated high p_T leptons and large $\not{E}_T$. To keep the event, it requires at least one pair of opposite-charged same-flavor leptons whose di-lepton invariant mass is within a mass window consistent with the Z boson. The dominant background sources are Z+jets, ZZ, $Z\gamma$ and $t\bar{t}$ productions. The di-lepton mass distribution of the selected events in the "*eee*" mode, from the CMS experiment, is shown in Figure 3. With a data sample of just a few hundreds of pb^{-1} of integrated luminosity at $\sqrt{s} = 14$ TeV, both experiments expect to achieve a five sigma level of significance for observing the WZ production. The spectra of the WZ transverse mass and the Z boson transverse momentum distributions are used to extract the WWZ anomalous parameters sensitivity at 95% C.L. , and are presented in Table 2.

Table 1: Expected 95% C.L. interval for anomalous coupling parameters from WW production by ATLAS.

WW, $\int L$ (fb^{-1})	1.0	10.0
$\Delta\kappa_Z$	[-0.117,0.187]	[-0.035,0.072]
λ_Z	[-0.108,0.111]	[-0.040,0.038]
Δg_1^Z	[-0.355,0.616]	[-0.149,0.309]
$\Delta\kappa_\gamma$	[-0.240,0.251]	[-0.088,0.089]
λ_γ	[-0.259,0.421]	[-0.074,0.165]

Table 2: Expected 95% C.L. interval for anomalous coupling parameters from WZ production by ATLAS.

WZ, $\int L$ (fb^{-1})	1.0	10.0
$\Delta\kappa_Z$	[-0.203,0.339]	[-0.095,0.222]
λ_Z	[-0.028,0.024]	[-0.015,0.013]
Δg_1^Z	[-0.021,0.054]	[-0.011,0.034]

2.3 $W\gamma$ Production

The $WW\gamma$ vertex can also be probed through the measurement of $W\gamma$ production. In the ATLAS and CMS studies, the signal events are selected in the leptonic decay channel of the W boson by requiring one isolated lepton (e or μ), one isolated photon and large $\not{E}_T$ in the final state of the event. The background consists of W+jets, Z+jets and $t\bar{t}$ productions, where one of the jets in the final state can fake as a photon, and $W+\gamma$ (γ radiated from the charged lepton of W decay) and $Z+\gamma$ (one of the two charged leptons from the Z boson decay is not identified) productions. The expected number of signal (background) events in 1 fb^{-1} of collected data at $\sqrt{s}$ = 14 TeV, for the ATLAS experiment, is 1604 (1183) for the electron decay channel, and 2166 (1342) for the muon decay channel. The photon transverse energy distribution, shown in Figure 4, is fitted to determine the 95% C.L. interval for the anomalous $WW\gamma$ coupling parameters, which are given in Table 3.

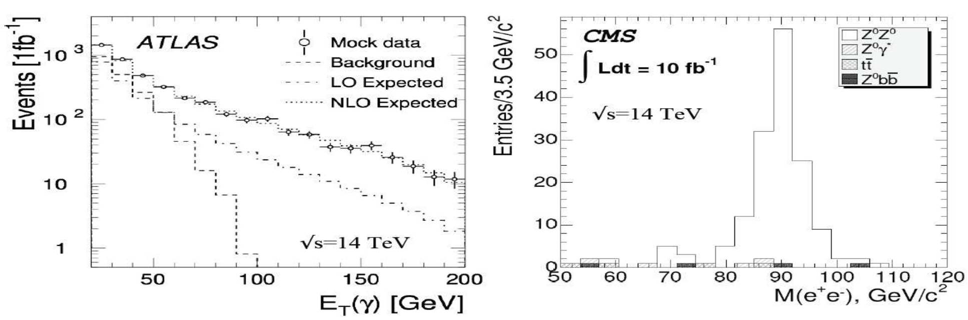

Figure 4: (LEFT) Simulated photon transverse energy distribution from $W\gamma$ production, and (RIGHT) e^+e^- invariant mass distribution of the $e^+e^-e^+e^-$ final state (two entries per event) in ZZ production.

2.4 ZZ Production

The ZZZ and $ZZ\gamma$ TGC's are forbidden in the SM. The test of their existence can be performed by measuring the production rate of a pair of ZZ bosons. The ATLAS and CMS experiments have performed simulation studies for ZZ production in the decay channels where each Z boson decays into a pair of e^+e^- or $\mu^+\mu^-$. The final state signatures can consist of $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$ or $\mu^+\mu^-\mu^+\mu^-$. ATLAS also considers the decay channel where one of the Z boson decays into a pair of e^+e^- or $\mu^+\mu^-$ and the other Z boson decays into a pair of $\nu\bar{\nu}$. The background mainly consists of Drell-Yan, Z+jets and $t\bar{t}$ productions. The expected number of signal events after all selection cuts for $l^+l^-l^+l^-$ final state, with an integrated luminosity of 1 fb^{-1} at $\sqrt{s}$ = 14 TeV, is $\sim$ 10 and with $\sim 0.2-0.4$ background events. The e^+e^- invariant mass distribution of the $e^+e^-e^+e^-$ final state from CMS, is shown in Figure 4. The p_T spectrum of the Z boson is used to determine the expected 95% C.L. interval for the anomalous neutral TGC parameters. These extracted values are given in Table 4.

Table 3: Expected 95% C.L. interval for anomalous coupling parameters from $W\gamma$ production by ATLAS.

$W\gamma$, $\int L$ (fb^{-1})	1.0	10.0
$\Delta\kappa_\gamma$	[-0.43,0.20]	[-0.26,0.07]
λ_γ	[-0.09,0.04]	[-0.05,0.02]

Table 4: Expected 95% C.L. interval for anomalous coupling parameters from ZZ production by ATLAS.

ZZ	ATLAS (10 fb^{-1})	LEP
f_4^Z	[-0.009,0.009]	[-0.30,0.30]
f_5^Z	[-0.009,0.009]	[-0.34,0.38]
f_4^γ	[-0.010,0.010]	[-0.17,0.19]
f_5^γ	[-0.011,0.010]	[-0.32,0.36]

Table 5: The 95% C.L. interval of the charged anomalous couplings sensitivities. The results from the LHC are determined with 10 fb^{-1} of integrated luminosity and at $\sqrt{s} = 14$ TeV. The "WZ" results from DØ experiment has made the assumption $\Delta g_1^Z = \Delta\kappa_Z$. The "$WW + W\gamma + WZ$" results from DØ and "$WW$" results from CDF and LEP experiments have made the assumptions $\lambda_\gamma = \lambda_Z$ and $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma * \tan^2\theta_W$.

Diboson	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WW (ATLAS)	[-0.040,0.038]	[-0.035,0.072]	[-0.149,0.309]	[-0.088,0.089]	[-0.074,0.165]
WZ (ATLAS)	[-0.015,0.013]	[-0.095,0.222]	[-0.011,0.034]		
$W\gamma$ (ATLAS)				[-0.26,0.07]	[-0.05,0.02]
WZ (DØ ,1 fb^{-1})	[-0.17,0.21]	[-0.12,0.29]			
$WW + W\gamma + WZ$ (DØ ,1 fb^{-1})			[-0.07,0.16]	[-0.29,0.38]	[-0.08,0.08]
WW (CDF, 3.6 fb^{-1})			[-0.22,0.30]	[-0.57,0.65]	[-0.14,0.15]
WW (LEP)			[-0.051,0.034]	[-0.105,0.069]	[-0.059,0.026]

3 Anomalous TGC from LHC and Other Experiments

Due to the higher energy reach and higher production rates at the LHC, the sensitivities to the anomalous TGC at the LHC is expected to be much better than at the Tevatron and at LEP. The expected 95% C.L. interval of the anomalous coupling sensitivities from measurements of the di-boson productions with 10 fb^{-1} of integrated luminosity and at $\sqrt{s} = 14$ TeV, are listed in Table 4 and 5. These values are compared to the recently published limits from the Tevatron and LEP experiments [4]. The values quoted in the tables show that many LHC limits are expected to be better than the current best limits from the Tevatron and LEP.

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