STUDIES OF DIBOSON PRODUCTION AND TRIPLE GAUGE BOSON COUPLINGS AT *LHC*

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We present a study of *WW*, *ZW* and *ZZ* production in *pp* collision at 14 *TeV* center-of-mass energy using electron and muon decay final states of the diboson pairs. Both *CMS* and *ATLAS* Collaboration have used full simulation data-sets that are based on *Geant-4* for the studies. *CMS* has studied $ZZ\to 4e$ and $ZW\to eee\nu$, $ee\mu\nu$, $e\mu\mu\nu$ and $\mu\mu\mu\nu$ channels; *ATLAS* has studies $WW\to e\nu\mu\nu$, $ZZ\to eeee$, $\mu\mu\mu\mu$, $ee\mu\mu$, $ZW\to eee\nu$, $ee\mu\nu$, $e\mu\mu\nu$ and $\mu\mu\mu\nu$ channels. It is expected that diboson *WZ*, *WW* and *ZZ* signals are to be established at *CMS* and *ATLAS* with 100 pb^{-1} ~1 fb^{-1} and the limits on the anomalous gauge boson couplings (*TGCs*) could be significantly improved over *Tevatron* results.

Keywords: gauge boson; triple gauge boson couplings.

1. Introduction

The diboson production cross section (σ_{VV}) can be predicted by the Standard Model (*SM*), calculating to the next leading order (*NLO*) and therefore the measurement of σ_{VV} is a direct test of the *SM*. On the other hand, the triple gauge boson couplings (*TGC*s) can be determined by the studies of dibson production of the $W^{\pm}\gamma$, $W^{\pm}Z$, and $W^{+}W^{-}$ processes. Measurements of these couplings provide stringent tests of the *SM* and provide important information about new physics beyond the *SM* since (*TGC*s) are completely fixed by the $SU(2)\times U(1)$ gauge structure of the *SM*[1-5]. In addition, the unknown electroweak symmetry breaking (*EWSB*) mechanism can be explored by studying diboson production. For example, the observation of resonance production of *ZZ*, $W^{+}W^{-}$, or $\gamma\gamma$ would be a signal for the *SM* Higgs boson, whereas enhanced production of longitudinally polarized *W* and *Z* pairs would be evidence for a strongly interacting *EWSB* scenario[6].

Diboson production is also important background that must be understood for many important new physics searches because new heavy particles, such as H^0, $H^{\pm}$, ρ_{TC}, η_{TC}, W', Z', *SUSY* particles and graviton (*G*) can decay into weak boson pairs[6].

Diboson productions and the existence of the corresponding *TGCs* have been verified by the experiments at *LEP* ($e^{+}e^{-}$ collider with $\sqrt{s}=200$ *GeV*) and *Tevatron* ($p\bar{p}$ collider with $\sqrt{s}=1.96$ *TeV*)[6]. This presentation briefly summarizes the studies on the diboson production at *LHC*, based on the full simulation data, using electron and muon final states of the diboson decays.

2. Monte Carlo data

CMS has studied $WZ\to\ell\ell\ell'$ ($\ell,\ell'=e,\mu$) and $ZZ\to\ell\ell\ell'\ell'$($\ell',\ell=e,\mu$), using the Monte Carlo data of the signals and major background events as shown in Table 1. The $t\bar{t}$ (2ℓ) is generated with *TopReX*, $Zb\bar{b}$ with *CompHEP* and all the others with *Pythia*.

ATLAS has studied the production of *WW*, *WZ* and *ZZ* from their leptonic decays to *e* and μ, based on the Monte Carlo data shown in Table 2. Diboson events and the $t\bar{t}$ background events are generated with *MC* programs *MC@NLO*(v2.3)+*Herweg*/*Jimmy*. For the diboson and $t\bar{t}$ events, one of the bosons or top quark is forced to decay leptonically and the other decays to all allowed final states. Except for $t\bar{t}$ events, background events are generated by *Pythia (V6.2)*, which performs *LO* calculations. *K-factors*, chosen by comparing the cross sections obtained from *MC@NLO* with that from *Pythia*, has been used in signal to background event normalizations.

Table 1. *CMS* full Monte Carlo simulation data for the studies of *ZZ* and *WZ*.

Process	σ×Br	k-factor
ZZ(4*e*)	18.7 fb	1.3
WZ(3ℓ,ℓ=*e*,μ,τ)	1.6 pb	1.92
$t\bar{t}$ (2 ℓ)	62.3 pb	1.6
Z(ee) $b\bar{b}$	60.3 pb	2.4
Z(μμ) $b\bar{b}$	60.3 pb	2.4
$t\bar{t}$ (4*e*)	194 fb	1.6
ZZ(2*e*2μ)	32.3 fb	1.35

Table 2. Monte Carlo data used by *ATLAS* for the diboson production studies. ℓ, ℓ' are *e* or *μ*.
* produced with Pythia 6.2.

Process	N_{MC}	Process	N_{MC}
ZW$^+$→2ℓ+X	26033	$t\bar{t}$ →ℓ+X	1.96×10^5
ZW$^-$→2ℓ+X	29085	Z→2e/2μ/2τ	2.30×10^6
ZZ→2ℓ2ℓ'	19933	W→ ℓν(ℓ=e,μ,τ)	1.61×10^6
W$^+$W$^-$→ℓν+X	32056	W+jet→2e/2μ/2τ	1.59×10^6
ZZ→2ℓ2ℓ' (*)	4.66×10^4	Z+jet→2e/2μ/2τ	5.80×10^6
Z $b\bar{b}$ →4ℓ	4.99×10^4	Drell –Yang	
		Z/γ→2e/2μ/2τ	1.67×10^7
Zγ→ 2ℓ	2.50×10^4	-	-

3. Preliminary results

3.1. *WZ*

CMS applied following criteria for signal event selection and background rejection:

- Three isolated electrons or muons with no lifetime and P_T>10 *GeV/c* and $|\eta|$<2.5
- *Z* candidate has the same flavor pair with opposite charge; the invariant mass satisfy $|M(\ell^+\ell^-) - M_Z(PDG)| < 20\ GeV/c^2$.
- *W* candidate from the third lepton satisfies $P_T > 20\ GeV/c$ and no jet with $E_T > 25\ GeV$.

Fig. 1 shows the invariant mass of the *Z* of *ZW* from selected e^+e^- pairs, and Table 3 lists the expected signal and background contributions, where $S_L = \sqrt{2\ln Q}$, and $Q = (1 + N_S / N_B)^{N_S+N_B} e^{-N_S}$. This definition is proper for the case when the background events are few.

Table 3. Expected signal and background yields of *WZ* for 1 fb^{-1} data from *CMS*.

Process	N_{eee}	$N_{\mu ee}$	$N_{e\mu\mu}$	$N_{\mu\mu\mu}$	N_t	ε (%)
$W^{\pm}Z \to \ell^{\pm}\ell^{+}\ell^{-}$	14.8	26.9	28.1	27.0	96.8	6.1
ZZ	0.63	1.54	1.50	1.51	5.19	4.7
$t\bar{t}$	0.93	1.55	-	0.31	2.79	0.02
$\mu^+\mu^- b\bar{b}$	-	-	6.54	4.9	11.4	0.005
$e^+e^- b\bar{b}$	1.21	1.82	-	-	3.03	0.005
Total bkg	2.8	4.9	8.0	6.7	22.5	-
S_L	5.3	7.3	6.5	6.6	12.8	-

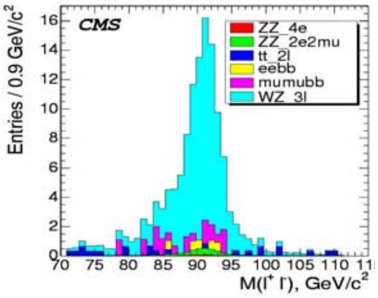

Fig. 1. Invariant mass of the $\ell^+\ell^-$ after event selection for 1 fb^{-1} data. All four channels listed in table 1 have been combined.

ATLAS select signal events containing three isolated energetic leptons (*e*, *μ*) with P_T>10 *GeV*, ΔR>0.2, of which two have opposite charge with the same flavor and their invariant mass is consistent with the mass of the *Z*. The third high P_T electron or muon with large missing transverse energy (E_T^{miss}>25 *GeV*) gives the *W* decay signal. Also required are that no more than one jet with energy greater than 30 *GeV* in the $|\eta| < 3$ region; the vector sum of the jet transverse energy calculated by summing the lepton E_T and missing energy must be less than 100 *GeV*, and the scalar sum of the jet transverse energy must be less than 200 *GeV*.

Fig. 2 shows the invariant mass of $Z_{\mu\mu}$ verse $W_{e\nu}$. The expected *ZW* signal and the background are listed in Table 4.

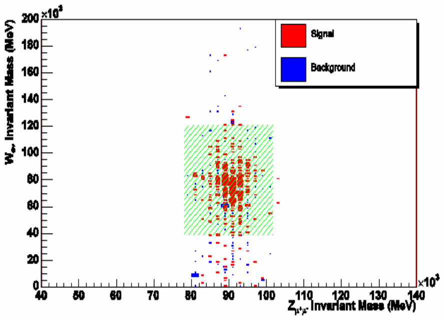

Fig. 2. Invariant of Z(μμ) verse W(eν). Signal events are within the hatched region (*ATLAS*).

Table 4. Expected *ZW* signal and backgrounds for 1 fb^{-1} data from *ATLAS*.

	N_{eee}	$N_{\mu ee}$	$N_{e\mu\mu}$	$N_{\mu\mu\mu}$	N_{tot}
N_s	16.9	17.1	21.9	19.8	75.7
N_b	1.71	0.88	1.73	2.00	6.32
S_L	7.43	8.62	8.93	8.03	16.40

3.2. *ZZ*

For the *ZZ* signal, one select four isolated high P_T electron or muon that come from the Z decays. *CMS* uses following criteria for the event selection:

- Four electron candidates ordered by P_T and satisfying P_T >30, 20, 15, 10 *GeV/c* and $|\eta|$<2.5
- *Z* candidate from e^+e^- pair and satisfies 50 *GeV* < $M(e^+e^-)$ < 120 *GeV*. Order *Z*'s according to nearness to M_Z and combine only the two non-overlapping *Z*'s.

The invariant mass of the $Z(e^+e^-)$ in the ZZ pair is plotted in Fig. 3, and the expected *ZZ* signal and the dominate background are listed in Table 5.

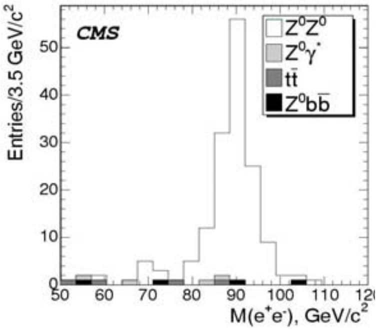

Fig. 3. Invariant mass of the e^+e^- after applying all cuts for 10 fb^{-1} data from *CMS*.

Table 5. Expected signal and background yields of *ZZ* for 1 fb^{-1} or 10 fb^{-1} data from *CMS*.

	ε(%)	$Ns/1fb^{-1}$	$Ns/10fb^{-1}$
ZZ	38	7.1	71.1
$Z\gamma$	4.5	0.16	1.60
$Zb\bar{b}$	0.07	0.08	0.84
$t\bar{t}$	0.06	0.12	1.22
Total bkg	-	0.36	3.66
S_L	-	4.8	13.1

Following are the criteria *ATLAS* applied for selecting *ZZ* signal:

- 2 lepton pairs with the same flavor but opposite charge are separated by $\Delta R(l^+l^-) >$ 0.2, and at least one lepton has $P_T > 25$ *GeV*.
- The invariant mass of the lepton pairs satisfying $|M_{l^+l^-} - M_Z(PDG)| < 12 GeV$.

For 1 fb^{-1} data, *ATLAS* finds 13 ZZ events with negligible background. The limited statistics of the Monte Carlo background of the *Z*+jets events is insufficient for *ATLAS* to estimate the background to *ZZ* final state with full simulation. The background has been previously studied in fast simulation [7], and is expected to be mainly $Zb\bar{b}$ events, at a level below *1%*.

3.3. *WW*

ATLAS studied the *WW* production in the decay channel $W^+W^- \to \ell^+\nu\ell^-\nu(\ell = e,\mu)$. The signal of the $W^+W^- \to \ell^+\nu\ell^-\nu$ process is two high-P_T leptons plus large missing transverse energy E_T^{miss} from the undetected neutrinos. Significant backgrounds to *WW* production in the dilepton decay channels include *DY* events with large missing transverse energy; *Z+jet* events where one lepton escapes detection (thus fake E_T^{miss}) and a jet fakes a lepton; and *W*+jet events in which the jet fakes a lepton.

- Two opposite charged leptons with high transverse momentum ($P_T > 20$ *GeV* and at least one lepton has $P_T > 25$ *GeV*) and larger missing energy ($E_T^{miss} > 30$, 35 and 40 *GeV* for e^+e^-, $e\mu$ and $\mu^+\mu^-$, respectively).
- No more than one jet with energy greater than 30 *GeV* in the $|\eta| < 3$ region; the vector sum and scalar sum of the jets transverse energy E_T must be less than 60 *GeV* and 45 *GeV*, respectively.
- The invariant masses of $\ell^+\ell^-$ ($\ell = e, \mu$) fulfills $|M_{l^+l^-} - M_Z| > 24(30)GeV$,also $M_{l_1l_2} > 50GeV$.
- The transverse mass of the W^+W^- is less than 500 *GeV* and the transverse momentum of the two leptons $p_T^{\ell_1\ell_2} > 30GeV$.
- $m_T^{\min} = \min(m_T^{\ell_1}, m_T^{\ell_2})$, the minimum transverse mass, must exceed 30 *GeV*, and the opening angle between the two leptons in the transverse plane is required to be $\Delta\phi_{\ell_1\ell_2} < 2.8$.

Fig. 4 indicates how the transverse momentum of the two selected lepton are used for rejecting background from *Z*+jet, *Z*+γ and *ZZ* processes.

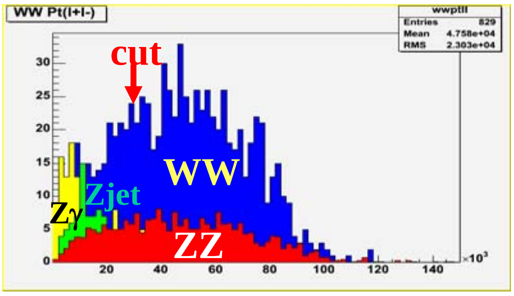

Fig. 4. Transverse momentum $P_T^{l_1l_2}$ of the two selected leptons (*ATLAS*).

For 1 fb^{-1} integrated luminosity data, the signal and background events of each channel are listed in Table 6. For the *ee* and $\mu\mu$ channels, the backgrounds are dominated by the *DY* and *Z*+jet processes. However, the $e\mu$ channel has very good detection sensitivity for the *WW* signal events because the rejection of background from *DY* process can be controlled well. Therefore this is the most promising channel for the *WW* studies.

Table 6. Expected *WW* signal and backgrounds for 1 fb^{-1} data from *ATLAS*.

	N_{ee}	$N_{\mu\mu}$	$N_{\mu e}$	N_{tot}
N_s	36.7	37.6	284.4	358.7
N_b	188.6	112.1	59.4	360.1
S_L	2.59	3.38	25.3	16.6
$N_s/\sqrt{N_b}$	2.67	3.55	36.9	18.9

4. Triple gauge boson couplings

Table 8 listed the *TGCs* limits from *D0* at *Tevatron* and *ATLAS* fast simulation data. The full simulation data gives similar *TGCs* limits. With the much higher energy provided by the *LHC*, the *ATLAS* experiment will improve the *TGC* measurements by orders of magnitude over *Tevatron* [7].

Table 8. *TGCs* from *D0* experiment and *ATLAS* fast simulation Monte Carlo data.

TGC	**D0** **(95% C.L.)**	**ATLAS Fast** **(30 fb^{-1})**
λ_γ	-0.22,0.22	-0.0035, 0.0035
λ_Z	-0.53, 0.56	-0.0073, 0.0073
	($\Delta K_Z = \Delta g_1^Z = 0$)	
$\Delta\kappa_\gamma$	-0.93, 0.97	-0.075, 0.076
$\Delta\kappa_Z$	-2.0, 2.4	-0.11, 0.12
	($\lambda_Z = \Delta g_1^Z = 0$)	
Δg_1^Z	-0.57, 0.76	-0.86, 0.011
	($\lambda_Z = \Delta\kappa_Z = 0$)	

The combined results with 68% confidence from *ALEPH*, *L3* and *OPAL* [8] are $\kappa_\gamma = 0.973^{+0.044}_{-0.045}$, $\lambda_\gamma = -0.028^{+0.020}_{-0.021}$, $g_1^Z = 0.984^{+0.022}_{-0.019}$.

5. Summary

CMS and *ATLAS* have studied diboson production with full Monte Carlo simulation data. The results are summarized in Table 8. *WZ*, *WW* and *ZZ* signals are expected to be established with early *LHC* data of about 100 pb^{-1}~$1fb^{-1}$; and anomalous gauge boson coupling can be probed with a few fb^{-1} data. Both experiments are further studying and optimizing the signal event selection and background rejection, and establishing the tools for the measurement of *TGCs* from the diboson production studies, as well as analyzing the systematic uncertainties.

Table 8. Expected signal and background with 1 fb^{-1} data from *CMS* and *ATLAS* experiments.

	CMS (N_s/N_b)	***ATLAS*** (N_s/N_b)
WW	-	284.4/59.4 (eμ)
ZZ	7.1/0.4 (4e)	13/0 (4e, 4μ, 2e2μ)
WZ(3ℓ, ℓ=e,μ)	97/23	75.7/6.3

The results of diboson production with *LHC* data will significantly improve our knowledge on the gauge boson production at hadron collider, and probe the triple gauge boson coupling at high energy, which may hint new physics if the measurement is inconsistent with the *SM* predictions.

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