Diboson studies at CMS

S. Duric([1]) for the CMS Collaboration
([1]) *Ruder Boskovic Institute, Zagreb, Croatia*

Summary. —
Measurements of diboson processes in proton-proton collisions at $\sqrt{s}$= 7 TeV and 8 TeV with the CMS experiment at the LHC are summarized. Inclusive cross section measurements are performed in the leptonic decay modes $ZZ \to 2l2l'$, $W\gamma \to l\nu\gamma$, $Z\gamma \to ll\gamma$, $Z\gamma \to \nu\nu\gamma$, $W^+W^- \to l\nu l\nu$, and semileptonic decay mode $WW+WZ \to l\nu jj$, where $l = e, \mu$ and $l' = e, \mu, \tau$. Cross section for ZZ (W^+W^-) production is measured at $\sqrt{s}$= 7 TeV and 8 TeV using data corresponding to an integrated luminosity of 5.0 fb^{-1} (4.9 fb^{-1}) and 5.3 fb^{-1} (3.5 fb^{-1}), respectively. Production of $W\gamma$, $Z\gamma$, $Z\gamma$, and $WW+WZ$ are measured at $\sqrt{s}$= 7 TeV using data of 5.0 fb^{-1}. A search for exclusive or quasi-exclusive W^+W^- production by two-photon exchange in the leptonic decay mode $WW \to e\nu\mu\nu$, at $\sqrt{s}$= 7 TeV is performed using data of 5.0 fb^{-1}. All measured cross sections are in agreement with NLO expectations. Inclusive diboson channels are used to extract upper limits on anomalous $WW\gamma$, WWZ, $ZZ\gamma$, $Z\gamma\gamma$, ZZZ trilinear gauge couplings. Limits on charged couplings are competitive to limits provided by previous experiments while neutral couplings limits are few times more precise. Exclusive W^+W^- channel is used to extract the limits on anomalous $\gamma\gamma WW$ quartic gauge coupling, set at the LHC for the first time and resulting in the sensitivity two orders of magnitude better then limits provided by LEP experiments.

PACS `14.70.Fm` – W bosons.
PACS `14.70.Hp` – Z bosons.
PACS `14.70.Bh` – Photons.

1. – Introduction

Electroweak processes are one of the base points for checking the validity of the standard model (SM). The Large hadron collider (LHC) has recently delivered collisions at a center of mass energy of 7 TeV and 8 TeV and has therefore allowed to test validity of standard model at TeV scale. Diboson processes provide a good opportunity to test SM at these energies.

Diboson processes are also the backgrounds for new physics and Higgs boson search measurements [1, 2]. It is of great importance therefore to measure these processes precisely. A precise measurement of the production of diboson events also provides direct information on trilinear gauge couplings (TGC) or quartic gauge couplings (QGC), the least well-measured couplings of the electroweak sector of the standard model. The self-interactions predicted among the gauge bosons in the SM determine all possible TGC and QGC, and any deviation from these values would be indicative of the presence of new physics.

This paper presents the results of diboson measurements with the CMS detector [3], including inclusive ZZ+X [4, 5], W^+W^-+X [5, 6], $W/Z\gamma$+X [7, 8], $WW+WZ+X$ [9] and exclusive W^+W^- [10] measurement. Upper limits on anomalous trilinear gauge coupling (aTGC) parameters and anomalous quartic gauge coupling (aQGC) parameters are extracted.

Measurement of ZZ+X (W^+W^-+X) production is performed at both available energies, of $\sqrt{s}$= 7 TeV and 8 TeV, using data corresponding to an integrated luminosity of 5.0(4.9) fb^{-1} and 5.3(3.5) fb^{-1}, respectively. All other diboson production channels are measured at energy of $\sqrt{s}$= 7 TeV using all collected data ($\approx$ 5 fb^{-1}), with the exception of WZ+X production which is measured using 1.0 fb^{-1} of data. Summary of used final states and phase space for cross section measurements is shown in Table I.

Except for the $WW+WZ$ process which is measured in the semileptonic final state, $WW+WZ \to l\nu jj$, all other processes are measured in the leptonic final state: $ZZ \to 2l2l'$, $W\gamma \to l\nu\gamma$, $Z\gamma \to ll\gamma$, $Z\gamma \to \nu\nu\gamma$, $W^+W^- \to l\nu l\nu$, where $l = e, \mu$ and $l' = e, \mu, \tau$. In the $WW+WZ$ process measurement the jet energy resolution does not allow to clearly separate $W \to jj$ from $Z \to jj$ therefore the measurement is performed as the sum of two processes. Compared to leptonic decay mode the semileptonic mode has worse signal over background ratio but the branching ratio is six times higher, allowing therefore to access higher transverse momentum (P_T) of boson and higher diboson masses which is very important for the sensitivity to aTGC.

A search for exclusive and quasi-exclusive W^+W^- production by two-photon exchange, $pp \to p^{(*)}\gamma\gamma p^{(*)} \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e\mu p^{(*)}$, is performed at $\sqrt{s}$= 7 TeV using data corresponding to an integrated luminosity of 5.0 fb^{-1}.

2. – Selection

The $ZZ \to 2l2l'$ final state is expected to have only a small contribution from background processes, therefore the selection is tuned to maximize the lepton reconstruction efficiency.

Measurement in $Z\gamma \to \nu\nu\gamma$ channel is performed in the region with high transverse energy of a photon, $P_T(\gamma)$ >145 GeV, due to the on-line selection. This region is however the most sensitive to aTGC. To reduce the background a high missing transverse energy and jet veto requirements are used.

In the selection of $W\gamma \to l\nu\gamma$ final state large transverse mass of W boson is required, $M_T(W)$ >70 GeV, due to on-line selection criteria. For reduction of the jet background a tight selection on the photon is required, for reduction of background from other diboson processes and Drell-Yan process a veto on events with second lepton is set. In $Z\gamma \to ll\gamma$ selection a mass of Z candidate is required to be $M(Z)$ >50 GeV.

The $WW \to l\nu l\nu$ channel is characterized with significant top-quark decay background, one of the selection requirements is therefore a zero high P_T jets in an event (jet veto). Contribution from Z events is reduced by Z mass window veto.

The selection of the $WW+WZ \to l\nu jj$ final state requires exactly two high transverse momentum jets ($P_T(jet)$ >35 GeV), significant missing transverse energy and exactly one isolated lepton with high P_T.

TABLE I. – *Summary of final states and cross section phase space of diboson measurements with the CMS.*

Final state	Cross section measurement phase space
$ZZ \to 2l2l'$	$60 < M_Z < 120GeV$ $pp \to ZZ + X$
$W\gamma \to l\nu\gamma$	$E^T_\gamma > 15/60/90GeV, \Delta R(l,\gamma) > 0.7$ $pp \to W\gamma \to l\nu\gamma + X$
$Z\gamma \to ll\gamma$	$E^T_\gamma > 15/60/90GeV, \Delta R(l,\gamma) > 0.7, M^Z > 50GeV$ $pp \to Z\gamma \to ll\gamma + X$
$Z\gamma \to \nu\nu\gamma$	$E^T_\gamma > 145GeV, \vert\eta^\gamma\vert < 1.4$ $pp \to Z\gamma \to \nu\nu\gamma + X$
$W^+W^- \to l\nu l\nu$	$pp \to W^+W^- \to l\nu l\nu + X$
$WW + WZ \to l\nu jj$	$pp \to WW + WZ + X$
$WZ \to l\nu ll$	$pp \to WZ + X$
$\gamma\gamma \to W^+W^- \to l\nu l\nu$	$pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e\mu p^{(*)}$
	$P_T(\mu, e) > 20GeV, \vert\eta^{\mu,e}\vert < 2.4, P_T(\mu e) > 100GeV$ $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e\mu p^{(*)}$

In exclusive $W^+W^- \to l\nu l\nu$ selection an opposite flavour channel is used since the background is much smaller than in the same flavour channel (due to $\gamma\gamma \to l^+l^-$ direct production and the Drell-Yan process).

3. – Background estimates

Dominant background for all inclusive diboson channels is estimated directly from data. Different methods for background estimation are used for different diboson processes. Other background processes with small contributions are usually estimated from the simulation.

One source of background is a misidentification of jets as leptons. A data control sample dominated with background is selected to measure the fake rate, the probability for a loosely-identified fake leptons to pass the tight selection. The fake rate is used to extrapolate the yield from a fake lepton sample to the fully selected leptons. This method is used to determine the W+jets contribution to the W^+W^- event selection and the Z+jet, WZ+jet and $t\bar{t}$ contributions to the ZZ event selection. Modified fake rate method is also used to determine the W+jet background in the exclusive W^+W^- measurement.

The dominant background source to the $W/Z\gamma$ arises from events with misidentified photons, originating mostly from jets in W/Z+jets events. A two component fit using the signal and background templates in discriminating observable, is used to determine this background contribution. In particular case of $W\gamma$ channel the correlation between the background template shape and the missing transverse energy in event is observed, causing one of the main systematic uncertainties on the measurement in this channel. The same background estimation method is used for the W+jets contribution to the

$WW + WZ$ channel. The signal and background contributions are determined by unbinned maximum likelihood fit on $M(jj)$ distribution after the full $WW + WZ$ selection. The template shape for background process W+jets is derived using the MADGRAPH generator [11]. In the fit the factorization and renormalization scale, and ME-PS matching scale, are floating, providing thus a good modeling of data.

The dominant background sources to the inclusive W^+W^- channel are processes $t\bar{t}$ and Wt. For background estimation the efficiency of selection requirement that vetos top events is measured and applied to background dominated data control sample.

In the exclusive W^+W^- measurement background contribution from hard-scattering W^+W^- process is estimated using the simulation. The agreement in the control sample with data is observed.

4. – Cross section measurements results

In $ZZ \to 2l2l'$ channel the data are in agreement with the SM expectations (NLO prediction with MCFM generator [12]) for both 7 TeV and 8 TeV proton collisions. The measurement is dominated by statistical uncertainty. Measured cross section in $Z\gamma \to \nu\nu\gamma$ channel is in agreement with NLO prediction from BAUR generator [13]. The measurement has a fairly large statistical uncertainty and systematic uncertainty dominated by background estimation and selection efficiency. Measurement in $Z\gamma \to ll\gamma$ and $W\gamma \to l\nu\gamma$ channels are performed in three different E_T^γ regions, $E_T(\gamma) > 15$ GeV, $E_T(\gamma) > 60$ GeV and $E_T(\gamma) > 90$ GeV. Measurements in $WW \to l\nu l\nu$ channel, for both 7 TeV and 8 TeV collisions, are dominated with systematic uncertainty, mainly from uncertainty on top-quark and W+jets background estimation and uncertainty on jet veto efficiency. Measured cross sections in $Z\gamma \to ll\gamma$, $W\gamma \to l\nu\gamma$ and $WW \to l\nu l\nu$ channels are in agreement with MCFM NLO prediction.

Measurement in the semileptonic channel $WW + WZ \to l\nu jj$ also agrees with the NLO expectations from MCFM generator. Significant statistical and large systematic uncertainty due to large background contribution are present. Significance of the observation is 4.3 standard deviations.

Two events are observed in the data after the exclusive W^+W^- selection, compared to a standard model expectation of 2.2±0.5 signal events with 0.84±0.13 background. The significance of the signal is 1.1 standard deviations, with upper limit on the cross section of 8.4 fb at 95% CL. Upper limit on the cross section is also set in the high $P_T(e\mu)$ region that is used for aTGC measurement.

All measured cross sections of diboson processes are in agreement with NLO expectations. The highest deviation is present in measurements in $W\gamma \to l\nu\gamma$ and $W^+W^- \to l\nu l\nu$ channels where the measured cross sections are one standard deviation higher then MCFM prediction. Summary of measured cross sections is shown in Figure 1.

5. – Trilinear and quartic gauge boson coupling measurements results

Anomalous couplings result in an increase of cross section at high boson P_T. The parametrization of anomalous contributions to TGC and QGC is used. For charged aTGCs, WWV couplings, different parametrizations have been used by different experiments. In the CMS measurements "LEP parametrization" [14, 15] is used. The approach without form-factor is used for aTGC while for aQGC both approaches, with and without form-factor, are used. Data show no signal of aTGC or aQGC, therefore the upper

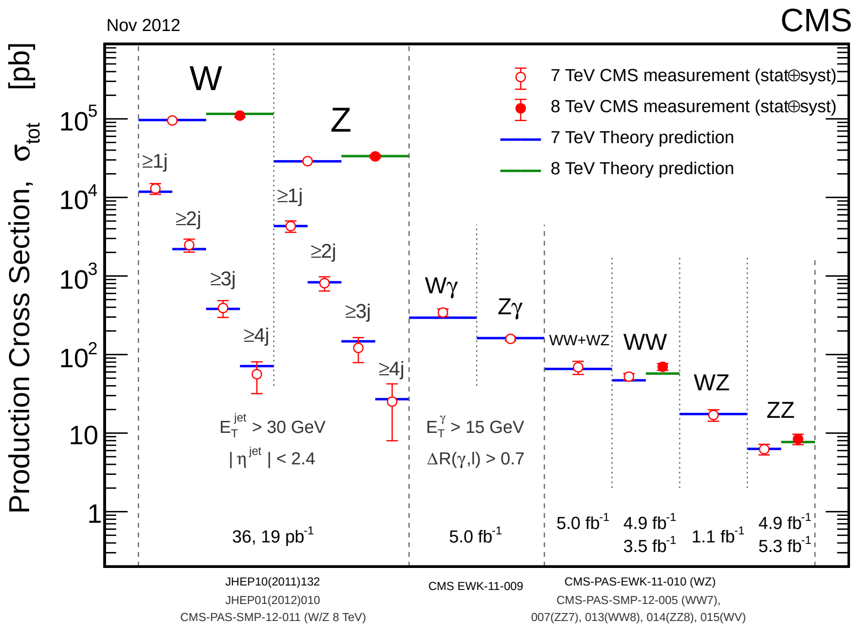

Fig. 1. – Summary of vector boson cross section measurements with the CMS.

limits on anomalous parameters are set. The profile likelihood criteria is used in inclusive W^+W^- channel, for all other channels limits are set with CLs criteria. One and two-dimensional limits at 95% CL on aTGC parameters are set. For one-dimensional limits, the parameter not being estimated is set to its SM value.

Limits on $ZZ\gamma$ and $Z\gamma\gamma$ are combined using two channels, $Z\gamma \to ll\gamma$ and $Z\gamma \to \nu\nu\gamma$. The sensitivity is driven by neutrino channel since there is no final state radiation contribution and the branching ratio for $Z \to \nu\nu$ is higher than for $Z \to ll$.

Figures 2 and 3 show the one-dimensional limits on aTGC parameters in comparison with results from ATLAS, Tevatron and LEP experiments [16]. CMS is probing charged aTGC parameters at competitive sensitivity to all previous experiments, limits on neutral aTGC parameters are few times more precise then limits provided by LEP experiments.

In the aQGC search region $P_T(\mu e) > 100$ GeV in exclusive W^+W^- channel, zero events are observed in data, consistent with the standard model expectation of 0.14. Upper limits on aQGC parameters are shown in Figure 4. The sensitivity exceeds LEP experiment sensitivity by two orders of magnitude.

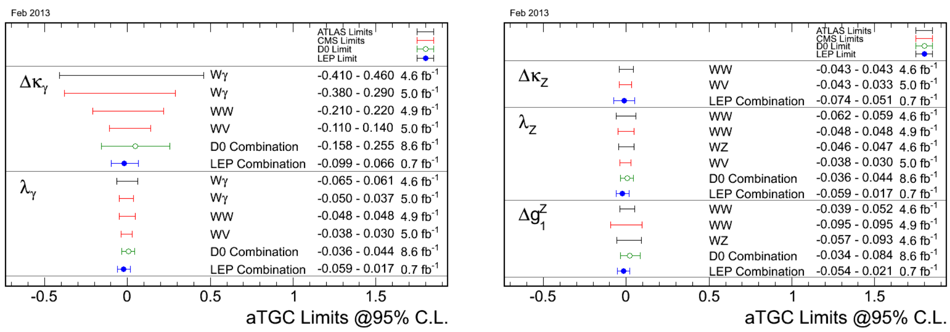

Fig. 2. – One-dimensional 95% CL limits on $WW\gamma$ (left) and WWZ (right) aTGC coupling parameters in comparison with limits from ATLAS, Tevatron and LEP experiments [16].

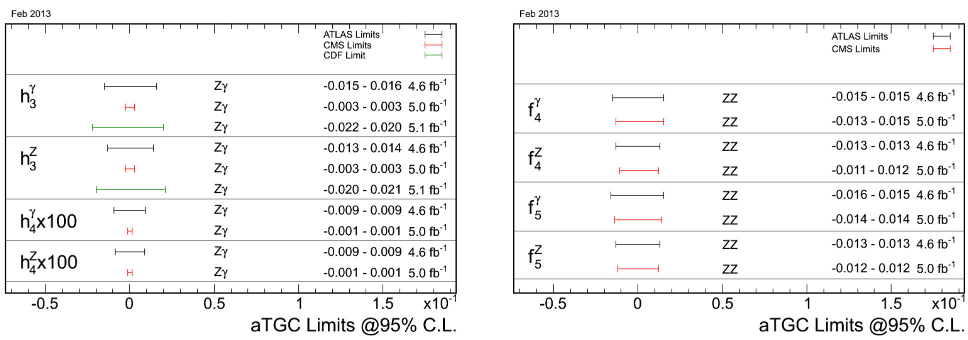

Fig. 3. – One-dimensional 95% CL limits on $Z\gamma\gamma, ZZ\gamma$ (left) and $ZZZ, ZZ\gamma$ (right) aTGC coupling parameters in comparison with limits from ATLAS, Tevatron and LEP experiments [16].

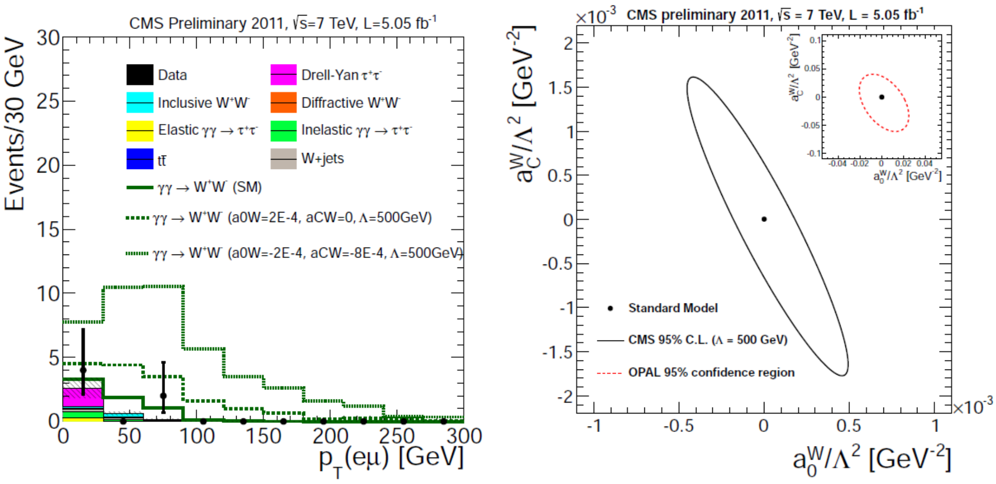

Fig. 4. – $P_T(e\mu)$ distribution for data and simulation in comparison with simulated aQGC signal in exclusive W^+W^- channel final state (left) and corresponding two-dimensional 95% CL limits on $\gamma\gamma WW$ aTGC coupling parameters (right) in comparison with limits from LEP experiments.

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