

## Diboson physics at ATLAS

K. BACHAS<sup>(1)</sup> ON BEHALF OF THE ATLAS COLLABORATION

<sup>(1)</sup> *Aristotle University of Thessaloniki - Nuclear and Particle Physics Laboratory, 54124 University Campus, Thessaloniki, Greece*

**Summary.** — This paper is intended to give an overview of the ATLAS results on the production cross sections of gauge boson pairs in their fully leptonic decay modes using data from  $pp$  collisions at  $\sqrt{s} = 7$  TeV for  $W\gamma, Z\gamma, WW, ZZ$  and  $WZ$  and  $\sqrt{s} = 8$  TeV for  $ZZ$  at the Large Hadron Collider. The cross sections are found to be in agreement with the expectation from the Standard Model within the estimated uncertainties. The production cross section measurements also allow for studies of anomalous triple gauge couplings for which 95% confidence limits are set.

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### 1. – Introduction

Measurements of vector boson pair production provide excellent tests of the electroweak sector of the Standard Model (SM). In the SM, Triple Gauge Couplings (TGC) are predicted at tree level only with charged bosons, while neutral ones are forbidden. The TGC vertex is completely fixed by the electroweak gauge structure and so a precise measurement of this vertex, through the analysis of diboson production, is essential to test the high energy behavior of electroweak interactions and to probe for possible new physics in the bosonic sector. Any deviation from gauge constraints can cause a significant enhancement in the production cross section at high diboson invariant mass due to anomalous triple gauge boson couplings (aTGC).

This note presents measurements of the diboson production cross sections in proton-proton collisions and limits on aTGC with the ATLAS experiment [1]. The following diboson pair final states were investigated:  $W\gamma, Z\gamma, WW, ZZ$  and  $WZ$ . A sample of integrated luminosity  $L = 4.6 \text{ fb}^{-1}$  of 2011 data at a center of mass energy  $\sqrt{s} = 7$  TeV was used for all diboson pair final states, while  $L = 5.8 \text{ fb}^{-1}$  of 2012 data at  $\sqrt{s} = 8$  TeV was also used for  $ZZ$ . All studies used the fully leptonic decay final states with  $Z \rightarrow ll$  and  $W \rightarrow l\nu$ , where  $l = e$  or  $\mu$ . The studies of  $Z\gamma$  and  $ZZ$  channels also considered  $\nu\nu\gamma$  and  $ll\nu\nu$  final states respectively.

### 2. – $W\gamma$ and $Z\gamma$ cross section measurements

The diboson candidate events are selected from the production processes  $pp \rightarrow l\nu\gamma + X$ ,  $pp \rightarrow ll\gamma + X$  and  $pp \rightarrow \nu\nu\gamma + X$ . These final states include the production of  $W$  and

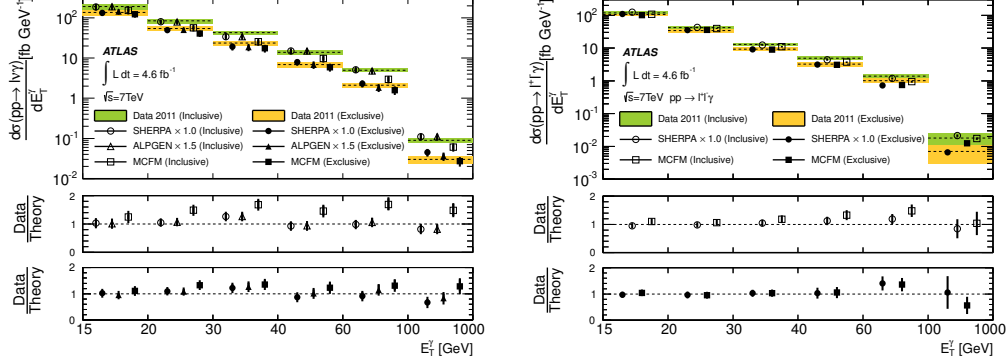


Fig. 1. – Measured  $E_T^\gamma$  differential cross sections of the  $pp \rightarrow l\nu\gamma$  (left) and  $pp \rightarrow ll\gamma$  (right) processes, using the combined electron and muon measurements in the inclusive ( $N_{\text{jet}} \geq 0$ ) and exclusive ( $N_{\text{jet}} = 0$ ) fiducial regions. The lower panes show the ratio of the data to the predictions by different generators. The Monte Carlo uncertainties are shown only in the ratio plots [2].

$Z$  bosons in association with photons from QED final State Radiation off the charged leptons, photons radiated from initial-state quarks, photons from the fragmentation of secondary quarks and gluons, and photons radiated by  $W$  bosons [2]. Two sets of cross section measurements are performed, namely the inclusive and exclusive, depending on the number of jets in the final state. The inclusive cross section measurement refers to production with no restriction on the recoil system. The exclusive measurement refers to events where no central jets with transverse energy  $E_T > 30$  GeV are produced. Jets are reconstructed from energy observed in the calorimeter cells using the anti- $kt$  jet clustering algorithm [3].

The experimental signature comprises a highly energetic isolated photon with  $E_T^\gamma > 15$  GeV plus missing transverse energy of  $E_T^{\text{miss}} > 35$  GeV for  $l\nu\gamma$  or two oppositely charged same-flavor leptons with an invariant mass greater than 40 GeV for  $ll\gamma$ . For the  $\nu\nu\gamma$  the requirements are  $E_T^\gamma > 100$  GeV and  $E_T^{\text{miss}} > 90$  GeV. In order to suppress Final State Radiation (FSR) contribution, the angular separation between the lepton and the photon is required to be  $\Delta R(l, \gamma) > 0.7$ .

The dominating background processes are  $Z$ +jets,  $W$ +jets and  $\gamma$ +jets but there are also contributions from  $t\bar{t}$  and  $WW$ . On fig. 1 the measured  $E_T^\gamma$  differential cross sections for  $pp \rightarrow W\gamma \rightarrow l\nu\gamma$  (left) and  $pp \rightarrow Z\gamma \rightarrow ll\gamma$  (right) are shown for both the inclusive and exclusive measurements. It is evident that Alpgen and Sherpa generators describe the  $W\gamma$  and  $Z\gamma$  distributions in data quite well for both topologies. The inclusive  $W\gamma$  measurement is underestimated by MCFM generator. The likely cause is the missing higher-order QCD contributions beyond the available NLO prediction. On the other hand for  $Z\gamma$  the agreement is quite good.

The systematic uncertainties on the cross sections are dominated by effects coming from the photon identification, background subtraction and jet energy scale uncertainties.

### 3. – $WW$ cross section measurement

The  $WW \rightarrow l\nu l\nu$  signal is measured in final states with two oppositely charged isolated leptons and large missing transverse energy [4]. The minimum requirement on

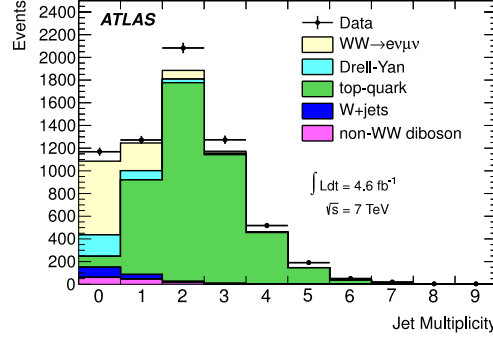


Fig. 2. – Jet multiplicity distribution of the  $e\mu$  topology from data and Monte Carlo simulation [4].

the  $p_T$  of the leptons is 25 GeV while for the missing transverse energy the  $E_{T,Rel}^{miss}$  variable is used, defined as:

$$(1) \quad E_{T,Rel}^{miss} = \begin{cases} E_T^{miss} \times \sin(\Delta\phi) & \text{if } \Delta\phi < \pi/2 \\ E_T^{miss} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

where  $\Delta\phi$  is the difference in the azimuthal angle between the  $E_T^{miss}$  direction and the nearest lepton or jet in the plane transverse to the beam. For the  $ee, \mu\mu$  and  $e\mu$  topologies the minimum  $E_{T,Rel}^{miss}$  requirement is 45, 45 and 25 GeV respectively. Fig. 2 shows the jet multiplicity distribution of the  $e\mu$  topology. Candidate  $WW$  events are required to have no jets reconstructed in the final state.

Processes that can mimic the  $ll + E_T^{miss}$  signal with no reconstructed jets are the top-quark production when additional jets in the final state fail reconstruction,  $W$ +jets when a jet fakes a lepton, Drell-Yan with mismeasured jets,  $WZ$  and  $ZZ$  processes when only two leptons are reconstructed in the final state, and the  $W\gamma$  process when the photon converts into electrons.

After applying the selection criteria 1325 events are observed and the total estimated background is  $369 \pm 31(\text{stat.}) \pm 53(\text{syst.})$  events, extracted from data-driven and MC based methods. The left distribution of fig. 3 shows the comparison of data and MC of the leading lepton  $p_T$  after all selection criteria are applied, while the one on the right shows the normalized fiducial cross section in bins of leading lepton  $p_T$ .

The measured total production cross section is  $51.9 \pm 2.0(\text{stat.}) \pm 3.9(\text{syst.}) \pm 2.0(\text{lumi.})$  pb while the theoretical prediction gives  $44.7_{-1.9}^{+2.1}$  pb. The driving uncertainty of the measurement is the systematics due to the jet veto requirement and the estimation of fake lepton backgrounds.

#### 4. – $ZZ$ cross section measurement

The analyses of  $Z$  boson pair production is performed in the  $4l$  and  $2l2\nu$  final states [5]. In the former topology the signature comprises of 4 isolated leptons with  $p_T$  starting from 7 GeV and the invariant mass of each reconstructed lepton pair is required to be in the mass window [66, 116] GeV. For the latter topology, the signature is 2 high- $p_T$  isolated leptons and axial- $E_T^{miss} > 75$  GeV, where the axial- $E_T^{miss}$  is the projection of  $E_T^{miss}$  along

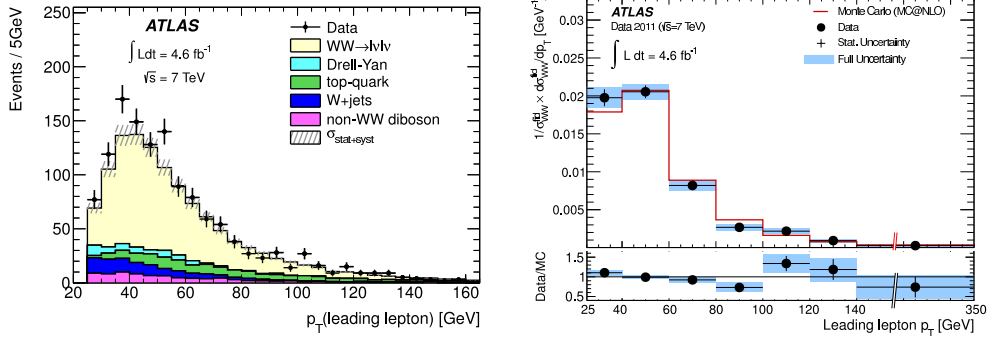


Fig. 3. – Left: Leading lepton  $p_T$  distribution for  $WW$  candidates with all selection criteria applied and combining  $ee$ ,  $\mu\mu$  and  $e\mu$  channels. Background contributions from the Drell-Yan, top-quark and  $W$ +jets processes are obtained from data-driven methods. The prediction of the SM  $WW$  contribution is normalized to the inclusive theoretical cross section of 44.7 pb [4]. Right: Normalized fiducial cross section together with the overall uncertainty in bins of the leading lepton  $p_T$ .

the opposite direction of the  $Z$ . The invariant mass of the two leptons should lie in the window [76, 106] GeV. Note that for the fiducial cross section results the  $ZZ^*$  case is also considered, where the invariant mass of the subleading lepton pair should be more than 20 GeV. In the left plot of fig. 4 the mass of the leading lepton pair versus the mass of the sub-leading lepton pair, is given. The right plot of fig. 4 shows the invariant mass of the 4-lepton system in the  $ZZ^*$  selection.

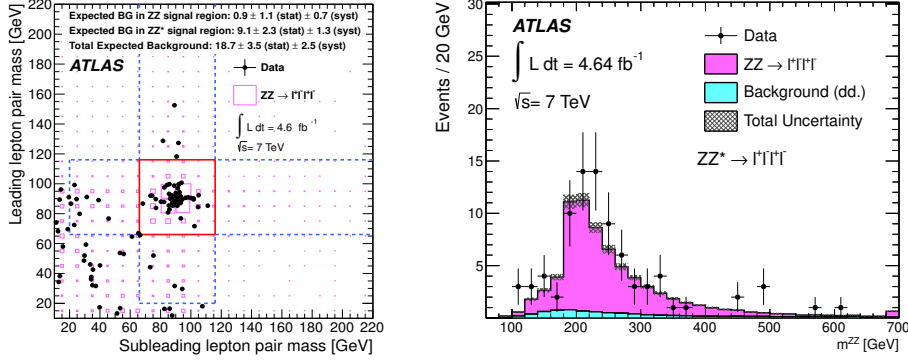


Fig. 4. – Left: The mass of the leading lepton pair versus the mass of the sub-leading lepton pair. The events observed in data are shown as solid circles and the  $ZZ^* \rightarrow llll$  signal prediction from simulation as boxes. The size of each box is proportional to the number of events in each bin. The region enclosed by the solid (dashed) lines indicates the signal region defined by the requirements on the lepton-pair masses for  $ZZ$  ( $ZZ^*$ ) events. Right: Invariant mass of the 4-lepton system for the  $ZZ^*$  selection. The points represent data and the histograms show the prediction from simulation, where the background is normalized to the data-driven estimate. The shaded band shows the combined statistical and systematic uncertainty on the prediction [5].

The  $4l$  final state is a very clean signature with small background contributions. These

mainly come from  $Z$ +jets and  $t\bar{t}$  processes where the jets are misidentified as leptons and they are estimated with data-driven methods. The background is more significant in the  $2l2\nu$  final state and is a mixture of diboson,  $t\bar{t}$  and Drell-Yan events.

After all event selections are applied, the observed yield in the  $4l$  final state is 66 (84) events in the  $ZZ$  ( $ZZ^*$ ) case with a background expectation of  $0.9 \pm 1.1$ (stat.)  $\pm 0.7$ (syst.) ( $9.1 \pm 2.3$ (stat.)  $\pm 1.3$ (syst.)). The corresponding yield for the  $2l2\nu$  final state is 87 events with background expectation of  $46.9 \pm 4.8$ (stat.)  $\pm 1.9$ (syst.). The total production cross section is measured in both 7 TeV and 8 TeV data, in the case where both  $Z$  bosons are on-shell. The results are summarized in fig. 5. For 7 TeV the total cross section is  $6.7 \pm 0.7$ (stat.)  $^{+0.4}_{-0.3}$ (syst.)  $\pm 0.3$ (lumi.) pb with theoretical prediction of  $5.89 \pm ^{+0.22}_{-0.18}$  pb. For

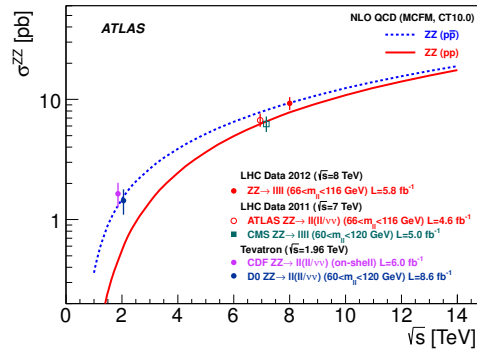


Fig. 5. – Measurements and theoretical predictions of the total  $ZZ$  production cross section as a function of center of mass energy  $\sqrt{s}$ . Experimental measurements from CDF and D0 in  $p\bar{p}$  collisions at the Tevatron at  $\sqrt{s} = 1.96$  TeV, and experimental measurements from ATLAS in  $pp$  collisions at the LHC at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV are shown. The blue dashed line shows the theoretical prediction for the  $ZZ$  production cross section in  $p\bar{p}$  collisions. The solid red line shows the theoretical prediction for the  $ZZ$  production cross section in  $pp$  collisions [6].

8 TeV the total cross section is  $9.3^{+1.1}_{-1.0}$ (stat.)  $^{+0.4}_{-0.3}$ (syst.)  $\pm 0.3$ (lumi.) pb with theoretical prediction  $7.4^{+0.4}_{-0.4}$  pb [6]. The main uncertainty of the measurement is statistical while the systematic uncertainty with the greatest contribution is the lepton reconstruction and isolation efficiency.

## 5. – $WZ$ cross section measurement

The analysis of  $WZ$  production is performed with  $3l\nu$  final states [7]. The signature of these topologies is 3 high- $p_T$  isolated leptons with  $p_T > 15, 15, 20$  GeV for the two leptons from  $Z$  and the one from the  $W$  respectively, and  $E_T^{miss} > 25$  GeV.

Main sources of background are the  $Z$ +jets and  $t\bar{t}$  events where the two leptons from the vector boson decays are accompanied by a jet which is misidentified as a lepton. These backgrounds are estimated from data-driven techniques. There is also contribution from  $ZZ$  background where one lepton falls outside the acceptance of the detector and thus creates  $E_T^{miss}$ . This source is estimated from MC. In fig. 6 the  $E_T^{miss}$  (left) and the invariant mass of the  $WZ$  system (right) are shown.

The presence of 3 leptons in the final state and the requirement of a tight invariant mass window for the  $Z$  leptons around the  $Z$  pole ( $|m_Z - m_{PDG}| < 10$  GeV) suppresses significantly the background. Imposing stricter selection criteria for the  $W$  lepton with

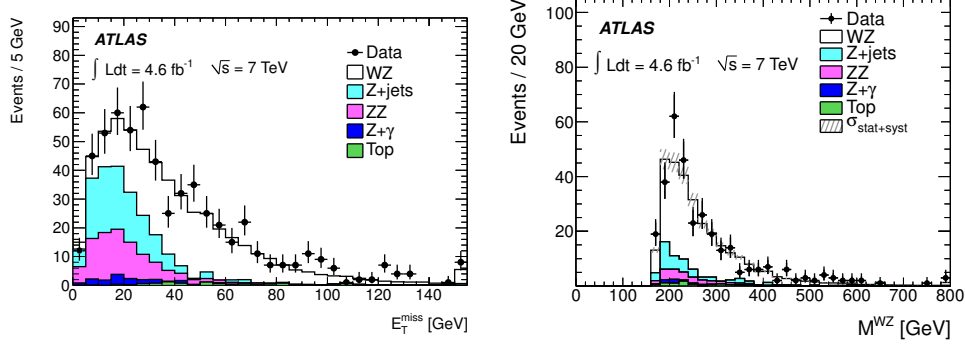


Fig. 6. – Left: Data and MC comparison of the  $E_T^{miss}$  distribution in trilepton events before applying the  $E_T^{miss}$  requirement. Right: Invariant mass  $m_{WZ}$  of the  $WZ$  pair. The shaded bands indicate the total statistical and systematic uncertainties of the prediction. For  $Z$ +jets and  $t\bar{t}$ , the expected shape is taken from simulation but the normalization is taken from the data-driven estimates. The rightmost bins include overflow [7].

respect to the leptons coming from the  $Z$  boson, suppresses the background coming from  $Z$ +jets and  $t\bar{t}$  even further.

Given the selection requirements, the total number of observed events is  $317$  with a background expectation of  $68 \pm 10$  events. Fig. 7 shows the normalized fiducial cross section in bins of  $p_T^Z$  (left) and  $m_{WZ}$  (right) compared to the SM prediction. The measured total production cross section is  $19.0^{+1.4}_{-1.3}(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.4(\text{lumi.})$  pb while the expectation from SM is  $17.6^{+1.1}_{-1.0}$  pb.

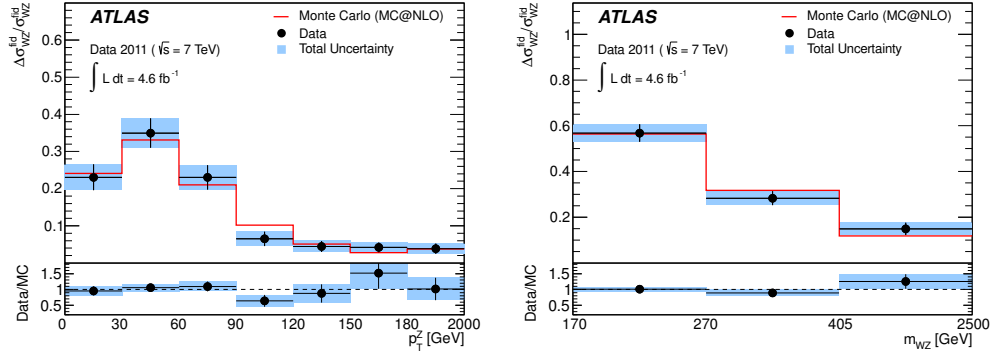


Fig. 7. – Normalized fiducial cross section in bins of  $p_T^Z$  (left) and  $m_{WZ}$  (right) compared to the SM prediction. The total uncertainty contains statistical and systematic uncertainties added in quadrature [7].

## 6. – Triple Gauge Couplings measurements

The effect of aTGC is modelled using an effective Lagrangian which depends on the parameters shown in table I [8, 9]. If aTGCs exist they are expected to modify the production rates and kinematics of the processes which would manifest as enhanced

production cross sections at high invariant mass and high- $p_T$ . Neutral aTGC are not allowed in the SM which predicts all parameters to be zero except for the charged aTGC parameters  $g_1^V$  and  $\kappa_1^V$  which are 1. In figs. 8 and 9 a summary of the limits set on the different aTGC parameters is shown along with comparisons to other experiments. Fig. 8 shows limits set by the  $W\gamma$ ,  $Z\gamma$  and  $WW$  analyses described before, while limits illustrated in fig. 9 are extracted from the  $ZZ$  and  $WZ$  analyses. No deviation from the expected SM values is observed in any channel.

interaction	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	$WW, W\gamma$
$WWZ$	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	$WW, WZ$
$ZZ\gamma$	$h_3^Z, h_4^Z$	$Z\gamma$
$Z\gamma\gamma$	$h_3^\gamma, h_4^\gamma$	$Z\gamma$
$Z\gamma Z$	$f_{40}^Z, f_{50}^Z$	$ZZ$
$ZZZ$	$f_{40}^\gamma, f_{50}^\gamma$	$ZZ$

TABLE I. – List of TGC parameters that enter in the effective Lagrangian for each diboson process.

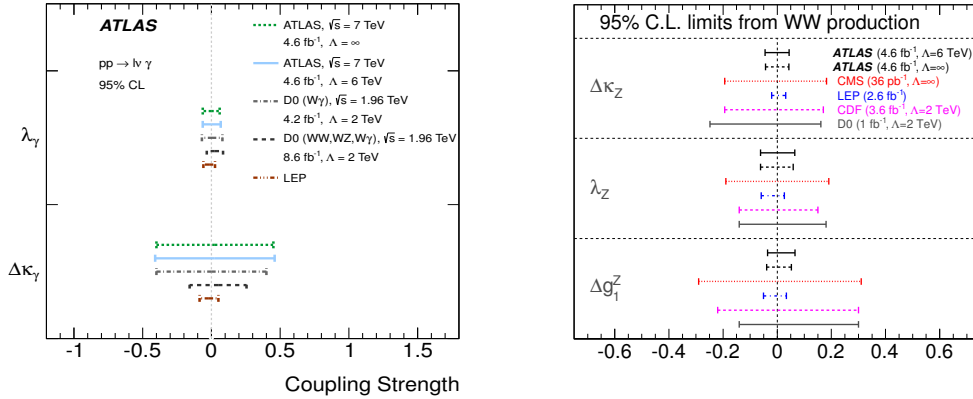


Fig. 8. – Left: 95% CL intervals for anomalous couplings from ATLAS, D0 and LEP for the charged aTGCs  $\Delta\kappa_\gamma$  and  $\lambda_\gamma$ . The ATLAS and D0 results from  $W\gamma$  production are shown. The LEP charged aTGCs results were obtained from  $WW$  production, which is also sensitive to the  $WWZ$  couplings. The combined aTGC results from D0 were obtained from  $WW + WZ \rightarrow \nu\gamma jj$ ,  $WW + WZ \rightarrow \nu\gamma ll$ ,  $W\gamma \rightarrow \nu\gamma\gamma$  and  $WW \rightarrow \nu\nu\nu$  events. The integrated luminosities and cut-off parameter  $\Lambda$  are shown. Except for the coupling under study, all other anomalous couplings are set to zero. Right: Comparison of aTGC limits from ATLAS, CMS, CDF, D0 and LEP experiments for the  $\Delta\kappa_Z$ ,  $\lambda_Z$  and  $\Delta g_1^Z$  using  $WW$  events [2, 4].

TGC limits from  $WW$  analysis approach the precision of the combination limits from LEP experiments. Because of the higher energy and production cross section at the LHC, limits are better than the Tevatron. Limits from  $ZZ$  analysis are significantly tighter than the LEP and D0 experiments. Limits from  $W\gamma$  analysis are looser than the ones set from LEP and D0. Finally, the aTGC limits from  $WZ$  analysis set on  $\Delta g_1^Z$  and  $\lambda_Z$  are tighter than Tevatron while for  $\Delta\kappa_Z$  approaches Tevatron's precision.

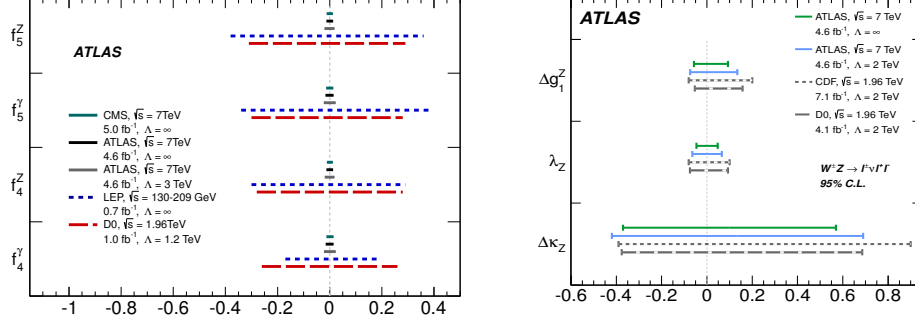


Fig. 9. – Left: Anomalous TGC 95% confidence intervals from ATLAS, CMS, LEP and Tevatron experiments using  $ZZ$  events. Right: Anomalous TGC limits at 95% confidence level from ATLAS, CDF, and D0 obtained from  $WZ$  production. Integrated luminosities, centre-of-mass energy and cut-off  $\Lambda$  for each experiment are shown on both plots [5, 7].

## 7. – Conclusions

Measurements of the production cross sections of  $W\gamma$ ,  $Z\gamma$ ,  $WW$ ,  $ZZ$  and  $WZ$  have been performed with the ATLAS detector at center-of-mass energy  $\sqrt{s} = 7$  TeV with 2011 LHC data and at  $\sqrt{s} = 8$  TeV with 2012 data for  $ZZ$ . The total production cross sections are compatible with the SM expectations within uncertainties. No evidence for new physics is observed from the kinematic distributions of the diboson processes. Limits on anomalous triple gauge couplings are set in all channels and values of aTGC parameters are well within the SM predictions.

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