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Diboson production

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Abstract. Measurements of diboson production cross sections in pp collisions at the LHC at a centre of mass energy $\sqrt{s}$ = 7 and 8 TeV, and in p$\bar{\text{p}}$ collisions at the Tevatron at $\sqrt{s}$ = 1.96 TeV are reviewed and compared with standard model predictions. Limits on charged and neutral anomalous triple gauge couplings extracted from the selected diboson event samples are also compared.

1 Introduction

The measurement of diboson production provides an important test of the standard model (SM), with any significant deviation from the measured cross sections giving an indication of new physics. In the SM, diboson production proceeds principally through the quark anti-quark annihilation process, shown in Figure 1. Triple gauge boson couplings (TGC) in the s-channel production mode are sensitive to new physics at a higher mass scale, which could change both the production rate and kinematics. In addition, measurements of diboson production are essential for an accurate estimate of irreducible backgrounds to the newly discovered resonance [1, 2] in the diboson decay modes.

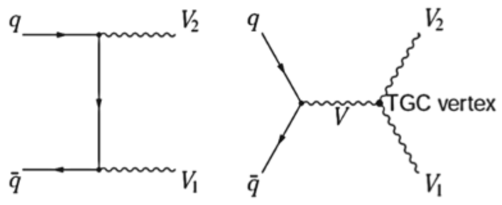

Figure 1. Diboson production in the t-channel (left) and s-channel (right).

Several recent results have been presented at this conference, using p$\bar{\text{p}}$ collision data from the Tevatron at a centre of mass energy $\sqrt{s}$ = 1.96 TeV, and in pp collisions at $\sqrt{s}$ = 7 and 8 TeV at the LHC. Cross section measurements are described in Section 2 and limits on anomalous triple gauge couplings are compared in Section 3.

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2 Cross Section Measurements

2.1 Wγ and Zγ final states

From the various diboson processes that can be produced at hadron colliders, the Wγ and Zγ final states have the highest yields, next to $\gamma\gamma$ production. The presence of either a W or Z boson improves the suppression of background processes, thus allowing stringent checks of the electroweak sector to be performed in these final sates.

Events are selected in the Wγ final state by requiring the presence of an electron or muon (ℓ), and missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ from the undetected neutrino, in addition to a photon. To suppress the contribution from final state radiation photons, measurements are reported for $\Delta R(\ell,\gamma) = \sqrt{d\eta^2 + d\phi^2} > 0.7$. The dominant background comes from W + jets events, where the jet is misidentified as a photon.

The ATLAS and CMS collaborations have performed measurements of $\sigma(\text{pp} \to \text{W}\gamma)$ at a centre of mass energy of $\sqrt{s}$ = 7 TeV, by using datasets corresponding to an integrated luminosity of 1.02 fb^{-1} and 5 fb^{-1} respectively. The ATLAS measurement of the inclusive cross section is 4.60 ± 0.11 (stat.) ± 0.64 (syst.) pb for photon $p_{\mathrm{T}} > 15$ GeV in an extended fiducial region, corresponding to the NLO SM prediction of 3.70 ± 0.28 pb [3]. The extended fiducial region requires the lepton and neutrino transverse momentum, p_{T}, to be above 25 GeV, and the lepton to be within pseudorapidity, $|\eta| < 2.47$, to emulate the experimental selection. The CMS collaboration has presented new results for this conference, measuring the inclusive cross section to be 37.0 ± 0.8 (stat.) ± 4.0 (syst.) ± 0.8 (lumi.) pb, to be compared with the NLO SM prediction of 31.81 ± 1.8 pb for photon p_{T} above 15 GeV[4]. The CDF and DØ collaborations have performed measurements of $\sigma(\text{p}\bar{\text{p}} \to \text{W}\gamma)$ by analysing datasets corresponding to an integrated luminosity of 1 fb^{-1} and 4.2 fb^{-1} respectively. The CDF

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collaboration measured 7.36 ± 0.35 (stat.) ± 0.75 (syst.) ± 0.43 (lumi.) pb to be compared with the NLO SM prediction for photons with p_T above 15 GeV and $|\eta| < 2.0$ of 8.2 ± 0.6 pb [5]. The DØ collaboration measured 7.6 ± 0.6 (stat.) ± 0.6 (syst.) pb to be compared with the NLO SM prediction of 7.6 ± 0.2 pb for photons with p_T above 15 GeV [6]. These results are compared in Figure 2.

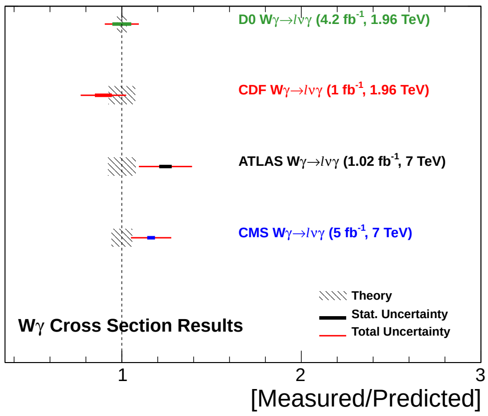

Figure 2. Summary of Wγ cross section measurements compared to standard model predictions.

In the Zγ analyses, events are selected by requiring a same flavor, opposite sign electron or muon pair ($\ell\ell$) with an invariant mass $M_{\ell\ell}$ close to the Z boson mass, in addition to a photon. The ATLAS collaboration has measured the inclusive $\sigma(\text{pp} \rightarrow Z\gamma)$ cross section of 1.29 ± 0.05 (stat.) ± 0.15 (syst.) pb to be compared with the NLO SM prediction of 1.23 ± 0.06 pb in the extended fiducial region [3]. The CMS collaboration has measured an inclusive cross section of 5.33 ± 0.08 (stat.) ± 0.25 (syst.) ± 0.12 (lumi.) pb to be compared with the NLO SM prediction of 5.45 ± 0.27 pb [4] for photon $p_T > 15$ GeV and $M_{\ell\ell} > 50$ GeV. The CDF collaboration has measured the inclusive $\sigma(\text{p}\bar{\text{p}} \rightarrow Z\gamma)$ cross section of 4.6±0.2 (stat.)±0.3 (syst.)±0.4 (lumi.) pb to be compared with the NLO SM prediction of 4.5 ± 0.4 pb in the fiducial region with photon p_T above 7 GeV and a dilepton invariant mass of at least 40 GeV [7]. The DØ collaboration measured 288 ± 15 (stat.) ± 11 (syst.) fb to be compared to the theoretical prediction of 294 ± 10 (PDF) $^{+1}_{-2}$ (scale) fb, with a requirement of $M_{\ell\ell\gamma} > 110$ GeV [8]. These results are compared in Figure 3.

The first measurement of Zγ production in the $\nu\nu\gamma$ final state in pp collisions at $\sqrt{s}$ = 7TeV has been presented by the CMS collaboration, using a dataset corresponding to an integrated luminosity of 5 fb^{-1}. This measurement is challenging because of large backgrounds from jets misidentified as photons, and instrumental sources such as beam-gas interactions. The Zγ production cross section is measured to be 21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb, where the photon is required to have $|\eta| < 1.4$ and $E_T > 145$ GeV, in agreement with the SM prediction of 21.9 ± 1.1 fb [9]. A previous measurement in this final

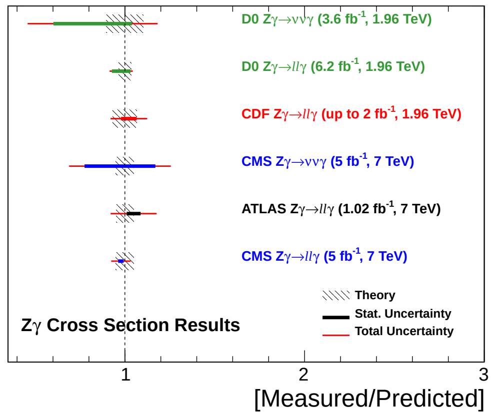

Figure 3. Summary of Zγ cross section measurements compared to standard model predictions.

state at $\sqrt{s}$ = 1.96 TeV in p$\bar{\text{p}}$ collisions was also presented. The DØ collaboration measured a cross section of 32 ± 9(stat. + syst. ± 2 (lumi.) fb to be compared with the NLO SM prediction of 39 ± 4 fb for photon p_T above 90 GeV [10]. These results are also compared in Figure 3.

2.2 WW and WZ final states

The ATLAS and CMS collaborations have measured the WW production cross section in the fully leptonic ($\ell\nu\ell\nu$) final state at $\sqrt{s}$ = 7 TeV, by using datasets corresponding to 4.6 fb^{-1} and 4.92 fb^{-1} respectively. CMS has also measured the production cross section in this final state at $\sqrt{s}$ = 8 TeV corresponding to an integrated luminosity of 3.54 fb^{-1}. The SM background sources to the W$^+$W$^-$ event sample in the $\ell\nu\ell\nu$ final state include W$\gamma^{(*)}$, top-quark (t$\bar{\text{t}}$ and tW), Z/$\gamma^* \rightarrow \ell^+\ell^-$, and diboson (WZ and ZZ) production, as well as W + jets and QCD multijet events, where at least one of the jets is misidentified as a lepton. The Z/$\gamma^* \rightarrow \ell^+\ell^-$ background is suppressed by requiring large E_T^{miss} and dilepton p_T, and the W + jets background is reduced by using stringent lepton identification and isolation requirements. The jet multiplicity distribution in the ATLAS event sample with two leptons of different flavor is shown in Figure 4. To minimise the contribution from the top-quark background, events containing jets are rejected. This leads to a significant theoretical uncertainty in the jet veto efficiency.

The ATLAS and CMS measurements of $\sigma(\text{pp} \rightarrow \text{WW})$ at $\sqrt{s}$ = 7 TeV are 51.9 ± 2.0 (stat.) ± 3.9 (syst.) ± 2.0 (lumi.) pb and 52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb, respectively [11] [12]. Both measurements are in agreement with the NLO SM prediction of 47.0 pb [13]. The CMS measurement at $\sqrt{s}$ = 8 TeV is 69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb, corresponding to the NLO SM prediction of $57.3^{+2.4}_{-1.6}$ pb [14]. The difference between the measured and theoretical value is (22 ± 13)% of the theoretical value.

The ATLAS, CMS, and DØ collaborations have also measured the total cross section of WW+WZ produc-

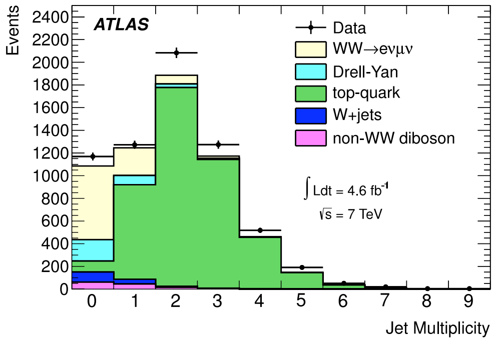

Figure 4. Comparison between the ATLAS WW $\rightarrow e\mu\nu$ data and simulation for the jet multiplicity before the jet veto requirement.

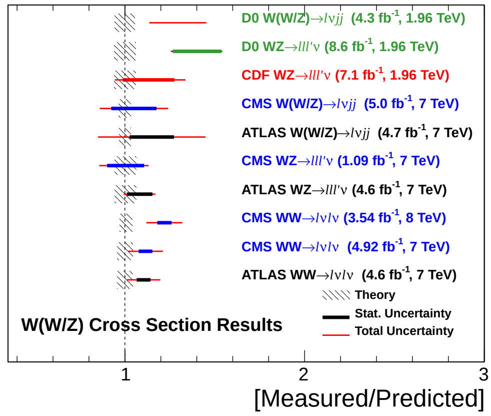

Figure 5. Summary of WW and WZ cross section measurements compared to standard model predictions.

tion by selecting events in the semi leptonic ($\ell\nu jj$) decay mode where one W boson decays leptonically and the other boson (W or Z) decays hadronically. This decay mode has a higher branching fraction compared to the fully leptonic mode, at the expense of introducing a larger background from W + jets events. The ATLAS and CMS measurements used datasets corresponding to an integrated luminosity of 4.7 fb^{-1} and 5 fb^{-1} at $\sqrt{s}$ = 7 TeV, and the DØ measurement used a dataset corresponding to 4.3 fb^{-1}. ATLAS measured $\sigma(pp \rightarrow (WW + WZ))$ to be 72 ± 9 (stat.) ± 15 (syst.) ± 13(MC stat.) pb using a dataset corresponding to 4.7 fb^{-1}, consistent with the SM expectation of 63.4 ± 2.6 pb. CMS measured 68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lumi.) pb [15]. The DØ collaboration measured $\sigma(p\bar{p} \rightarrow (WW + WZ))$ to be $19.6^{+3.2}_{-3.0}$ pb, compared with the NLO SM prediction of 15.2 ± 0.85 pb [16].

Measurements of WZ production in the fully leptonic ($\ell\nu\ell\ell$) final state have high purity after requiring three high p_T leptons, two of which are same flavor and have an invariant mass close to the Z boson, and large E_T^{miss} from the W decay. Because the branching ratio to this final state is smaller, these measurements are dominated by the statistical uncertainty in the selected event sample. The ATLAS and CMS collaborations have performed measurements of $\sigma(pp \rightarrow WZ)$ at $\sqrt{s}$ = 7 TeV by analysing datasets corresponding to an integrated luminosity of 4.6 fb^{-1} and 1 fb^{-1} respectively. ATLAS measured a total cross section of $19.0^{+1.4}_{-1.3}$ (stat.) ± 0.9 (syst.) ± 0.4 (lumi.) pb compared with the NLO SM prediction of $17.6^{+1.1}_{-1.0}$ pb for the dilepton invariant mass range $66 < M_{\ell\ell} < 116$ GeV for $Z \rightarrow \ell\ell$ [17]. CMS measured a total cross section of 17.0 ± 2.4 (stat.) ± 1.1 (syst.) ± 1.0 (lumi.) pb, which agrees well with an NLO SM prediction of 19.790 ± 0.088 pb [18]. The CDF and DØ measurements of $\sigma(p\bar{p} \rightarrow WZ)$ are $3.94^{+0.60}_{-0.53}$ (stat.)$^{+0.59}_{-0.46}$ (syst.) pb, and 4.50 ± 0.61 (stat.)$^{+0.16}_{-0.25}$ (syst.) pb for $60 < M_{\ell\ell} < 120$ GeV, in datasets corresponding to 7.2 fb^{-1} and 8.6 fb^{-1} respectively [19] [20]. The CDF measurement is in good agreement with the NLO SM prediction of 3.50 ± 0.21 pb, and the DØ measurement is slightly larger than, but still consistent with the NLO SM prediction of 3.21 ± 0.19 pb. These results are displayed graphically, compared with standard model predictions in Figure 5.

2.3 ZZ final state

Measurements of ZZ production have been performed in the clean, but statistically limited four-lepton ($\ell^+\ell^-\ell^+\ell^-$) final state by the ATLAS, CMS, CDF and DØ collaborations. Because the branching ratio for this final state is small, the precision of the measurements can be improved by combining with higher branching ratio final states in which one of the Z bosons decays either invisibly or to τ leptons.

The ATLAS collaboration measured $\sigma(pp \rightarrow ZZ)$ 6.7 ± 0.7 (stat.)$^{+0.4}_{-0.3}$ (syst.) ± 0.3 (lumi.) pb, by combining the four-lepton results with a measurement where of the Z bosons decays invisibly in the dilepton + E_T^{miss} final state, both using a dataset corresponding to 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV. This result is consistent within uncertainties with the NLO SM prediction of $5.89^{+0.22}_{-0.18}$ pb in the fiducial region $66 < M_{\ell\ell} < 106$ GeV [21]. The CMS collaboration measured $6.24^{+0.86}_{-0.80}$ (stat.)$^{+0.41}_{-0.32}$ (syst.) ± 0.14 (lumi.) pb in the fiducial region $60 < M_{\ell\ell} < 120$ GeV, including both four-lepton events and those where the second Z boson decays to τ leptons. This result is consistent with the NLO SM prediction of 6.3 ± 0.4 pb [22].

ATLAS measured $9.3^{+1.1}_{-1.0}$ (stat.)$^{+0.4}_{-0.3}$ (syst.) ± 0.3 (lumi.) pb in the four-lepton final state by using a dataset corresponding to 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV . This measurement is in agreement with the NLO SM prediction of 7.4 ± 0.4 pb in the fiducial region where the leading lepton has $p_T > 25$ GeV, the invariant mass of both opposite-sign same-flavor lepton pairs is between $66 < M_{\ell\ell} < 106$ GeV and electrons (muons) are required to be in $|\eta| < 2.47$ (2.50) [23]. CMS has measured 8.4 ± 1.0 (stat.) ± 0.7 (syst.) ± 0.4 (lumi.) pb using a dataset corresponding to 5.26 fb^{-1}, including both four-lepton and two lepton two τ events, to be compared with the the NLO SM prediction of 7.7 ± 0.4 pb in the fiducial region $60 < M_{\ell\ell} < 120$ GeV [14].

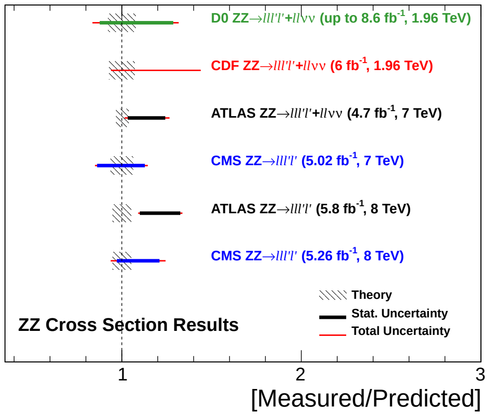

Figure 6. Summary of ZZ cross section measurements compared to standard model predictions.

The CDF and DØ collaborations measured $\sigma(p\bar{p} \to ZZ)$ by using datasets corresponding to 6 fb^{-1} and up to 8.6 fb^{-1} respectively. Both measurements are combinations of results in the four-lepton and two lepton + E_T^{miss} final states. CDF measured $1.64^{+0.44}_{-0.38}$ (stat + syst) pb, which is consistent with the NLO SM prediction of 1.4 ± 0.1 pb [24]. Equivalently, DØ measured $1.44^{+0.31}_{-0.28}$ (stat.) $\pm^{+0.17}_{-0.19}$ (syst.) pb [20].

The ZZ cross section measurements are summarised in comparison with the relevant theoretical predictions in Figure 6.

The CMS collaboration has performed the first observation of $Z \to 4\ell$ decays in pp collisions at $\sqrt{s} = 7$ TeV, by analysing a dataset corresponding to an integrated luminosity of 5.02 ± 0.11 fb^{-1}. The signal, shown in Figure 7, was observed with a statistical significance of 9.7σ [25]. The measured branching fraction is $\mathcal{B}(Z \to 4\ell) = \left(4.2^{+0.9}_{-0.8}(\text{stat.}) \pm 0.2(\text{syst.})\right) \times 10^{-6}$, in agreement with the SM prediction of 4.45×10^{-6}. The measured cross section times branching fraction is $\sigma(pp \to Z)\mathcal{B}(Z \to 4\ell) = 112^{+23}_{-20}(\text{stat.})^{+7}_{-5}(\text{syst.})^{+3}_{-2}(\text{lumi.})$, which is also in agreement with the SM prediction of 120 fb^{-1}. These measurements were performed with the four-lepton invariant mass restricted to $80 < m_{4\ell} < 100$ GeV and the two-lepton invariant mass restricted to $m_{\ell\ell} > 4$ GeV for all pairs of leptons. In addition, because the $Z \to 4\ell$ gives a narrow resonant peak in the four-lepton invariant mass distribution, this channel can be used to calibrate the four-lepton mass scale and low p_T lepton identification efficiencies for Higgs boson measurements in the $ZZ \to 4\ell$ decay mode.

3 Limits on anomalous triple gauge couplings

Diboson production is sensitive to triple gauge couplings in the s-channel production modes. Deviations of the triple gauge couplings from the SM values are referred to as anomalous triple gauge couplings (aTGC), which are parameterised by adding terms to the SM Lagrangian. The presence of aTGC will modify both the production rate

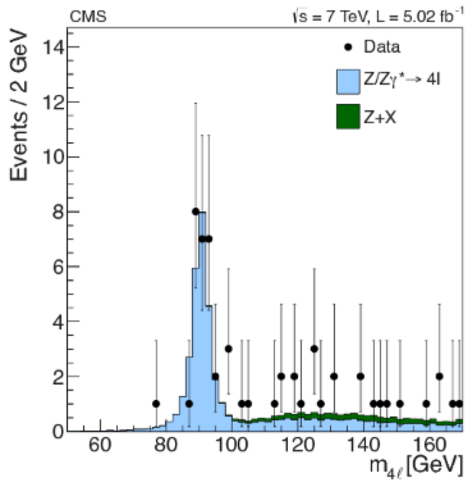

Figure 7. Four-lepton invariant mass distribution for events passing all selection requirements except that on $m_{4\ell}$. The data are shown by points. The filled histograms represent SM expectations for $pp \to Z/Z\gamma^\star \to 4\ell$ and for reducible backgrounds. The three final states, 4e, 4μ, and $2e2\mu$ are combined.

and kinematics from SM expectations. To prevent the total production cross section violating unitarity, a form factor is introduced to turn off the effect of each parameter above a cut off scale Λ. As the experimental sensitivity to aTGC increases, so does the scale at which unitarity violation would occur for permitted aTGC values.

Experimental measurements have been made by the ATLAS, CMS, CDF and DØ collaborations, leading to limits on charged and neutral aTGC. These limits are now summarised and compared.

4 Charged couplings

For the $WW\gamma$ vertex, the aTGC parameters are chosen to be λ_γ and $\Delta\kappa_\gamma = \kappa_\gamma - 1$, which are zero in the SM [26]. By using the photon p_T spectrum in the $W\gamma$ final state, CMS, ATLAS,and DØ have set limits on aTGC in the $WW\gamma$ vertex [4], [3] [6]. ATLAS and CMS have set limits by using the leading lepton p_T in the fully leptonic WW final state, which is also sensitive to the $WW\gamma$ vertex [11] [27]. By exploiting the higher branching ratio semi leptonic final state, CMS has set stringent limits from the dijet p_T spectrum [15]. These results are summarised graphically in Figure 8. The LHC measurements are now almost the most stringent, with LEP still providing more stringent limits on $\Delta\kappa_\gamma$ [28].

The aTGC parameters for the $WW\gamma$ and WWZ vertices are chosen to be $\Delta g_1^Z = g_1^Z - 1$, $\Delta\kappa_Z = \kappa_Z - 1$, $\Delta\kappa_\gamma = \kappa_\gamma - 1$, λ_Z and λ_γ, which are zero in the SM [29]. In the LEP parameterisation, $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa\gamma \cdot tan^2\theta_W$ [30]. Limits have been set by the ATLAS, CMS, CDF and DØ collaborations [17] [27] [19] [31]. The recent DØ results include the combination of the $W\gamma$, WW and WZ final states to increase sensitivity. The results are compared in Figure 9. No deviation from the SM is observed.

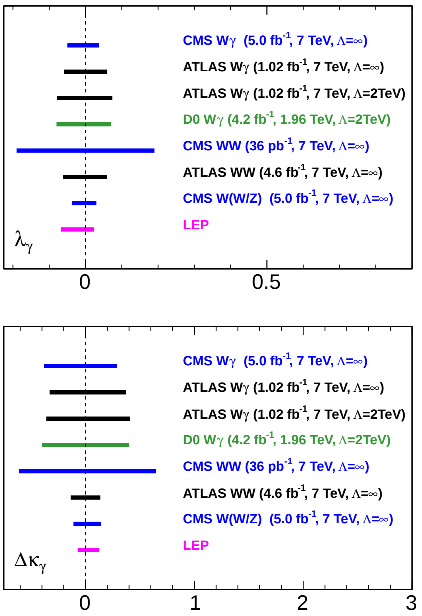

Figure 8. Summary of limits on anomalous WWγ triple gauge couplings measured in the Wγ and WW final states.

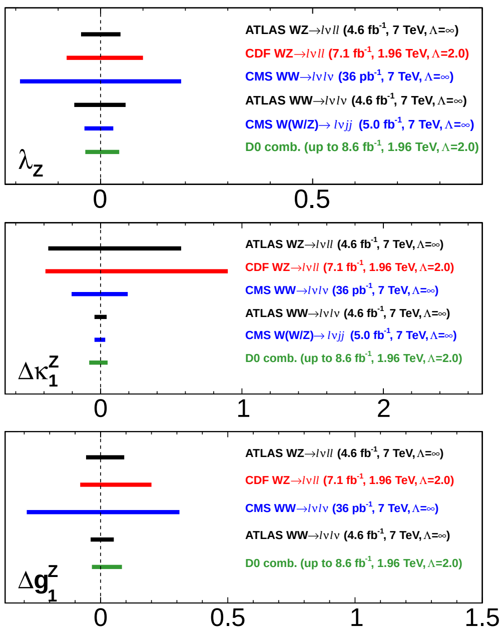

Figure 9. Summary of limits on anomalous WWγ and WWZ triple gauge couplings measured in the Wγ, WW and WZ final states.

4.1 Neutral couplings

The aTGC parameters for the ZVγ vertex, where V = Z or γ, are chosen to be h_3^V and h_4^V [32]. Limits have been set by both ATLAS and CMS, CDF and DØ, by using the photon p_T spectrum in the Zγ final state [3] [9] [7] [8]. In new results presented at this conference, the CMS collaboration are able to improve the limit by combining the results from

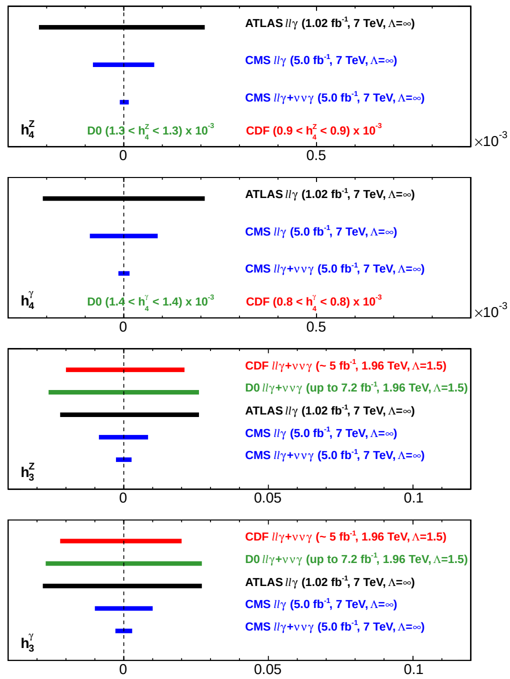

Figure 10. Summary of the limits on anomalous ZZγ and Z$\gamma\gamma$ triple gauge couplings measured in the Zγ final state.

the $\ell\ell\gamma$ and $\nu\nu\gamma$ final states. The results, which agree with SM expectations, are summarised in Figure 10.

The aTGC parameters for ZZ production are chosen to be h_4^V and f_5^V, which are zero in the SM [33]. This final state is unique in providing access to the ZZZ coupling. No evidence of aTGC is found, so limits have been set. ATLAS has improved on its previous result [34] by a factor of around five in new results presented at this conference, by increasing the size of the dataset used, adding the dilepton + E_T^{miss} final state, and by using the Z boson p_T spectrum instead of performing a single counting experiment [21]. The CMS limits are set by using the four-lepton invariant mass distribution [22]. These results are compared in Figure 11.

5 Conclusion

Measurements of diboson production by the ATLAS, CMS, CDF and DØ experiments have been presented, covering different production modes and centre of mass energies. The measured production cross sections are typically in agreement with SM predictions, with a typical precision comparable to or better than the size of NLO corrections [13]. Events selected in these channels have been used to constrain new physics, by setting limits on anomalous triple gauge couplings. Measurements from the LHC experiments now provide the most sensitive limits in most channels. The emergence of channel combinations from both the Tevatron experiments and the LHC, continues to increase sensitivity to aTGC.

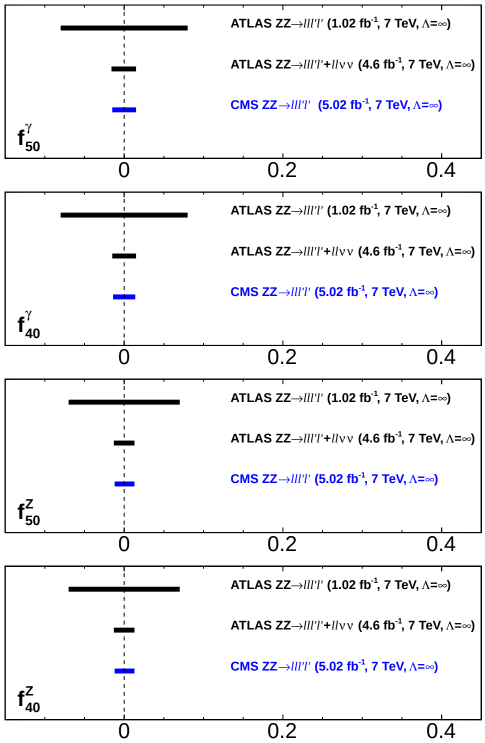

Figure 11. Summary of the limits on anomalous ZZZ and ZZγ triple gauge couplings measured in the Zγ final state.

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