

# Combined Limits on Anomalous Couplings at DØ

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We present the first combination of limits across different diboson production processes using  $1 \text{ fb}^{-1}$  of data collected by the DØ detector at the Fermilab Tevatron collider. We set the most stringent limits on anomalous values of the  $\gamma/ZWW$  couplings at a hadron collider and present the most stringent measurements to date for the  $W$  boson magnetic dipole and quadrupole moments.

## 1 Phenomenology

Study of the vector bosons interactions and the trilinear gauge boson couplings (TGCs) [1] provides a test of the electroweak sector of the Standard Model (SM). Any deviation from predicted SM values could indicate New Physics (NP). The TGCs contribute to diboson production via  $s$ -channel diagram. Thus, production of  $WW$  contains two trilinear vertices,  $\gamma WW$  and  $ZWW$ , while the  $WZ$  production contains the  $ZWW$  vertex only. The effective lagrangian which describes  $\gamma/ZWW$  vertices contains 14 charged TGCs which are grouped according to the symmetry properties into  $C$  (charge conjugation) and  $P$  (parity) conserving couplings. In the SM all couplings vanish except  $g_1^V = \kappa_V = 1$  ( $V = \gamma/Z$ ). The value of  $g_1^\gamma$  is fixed by electromagnetic (EM) gauge invariance ( $g_1^\gamma = 1$ ) while the value of  $g_1^Z$  may differ from its SM value. Considering the  $C$  and  $P$  conserving couplings only, five couplings remain, and their deviations from the SM values are denoted as the anomalous TGCs:  $\Delta g_1^Z$ ,  $\Delta \kappa_\gamma$ ,  $\Delta \kappa_Z$ ,  $\lambda_\gamma$  and  $\lambda_Z$ . Couplings  $g_1^Z$ ,  $\kappa_\gamma$  and  $\lambda_\gamma$  also relate to the  $W$  boson magnetic dipole moment  $\mu_W$  and electromagnetic quadrupole moment  $q_W$  as  $\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$  and  $q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$ . Anomalous TGCs could cause an unphysical increase in diboson production cross sections as the center-of-mass energy,  $\sqrt{\hat{s}}$ , approaches NP scale,  $\Lambda_{NP}$ . These divergences are controlled by a form factor  $\Delta a(\hat{s}) = \Delta a_0/(1 + \hat{s}/\Lambda_{NP}^2)^n$  for which the anomalous coupling vanishes as  $\hat{s} \rightarrow \infty$ . The coupling  $a_0$  is a low-energy approximation of the coupling  $a(\hat{s})$  and  $n = 2$  for  $\gamma WW$  and  $ZWW$  couplings.

Because experimental evidence is consistent with the existence of an  $SU(2)_L \times U(1)_Y$  gauge symmetry, it is reasonable to require the effective lagrangian to be invariant with respect to this symmetry. This gauge-invariant parametrization [2] gives the following relations between the  $\Delta \kappa_\gamma$ ,  $\Delta g_1^Z$  and  $\lambda$  couplings:  $\Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa_\gamma \cdot \tan^2 \theta_W$  and  $\lambda = \lambda_Z = \lambda_\gamma$ . We refer to this relationship as the  $SU(2)_L \times U(1)_Y$  respecting scenario with three different parameters,  $\Delta \kappa_\gamma$ ,  $\lambda$  and  $\Delta g_1^Z$ .

A second interpretive scenario, referred to as the equal couplings ( $ZWW = \gamma WW$ ) scenario [3], specifies the  $\gamma WW$  and  $ZWW$  couplings to be equal. In this case,  $\Delta g_1^Z = \Delta g_1^\gamma = 0$  and the relations between the couplings become:  $\Delta \kappa = \Delta \kappa_Z = \Delta \kappa_\gamma$  and  $\lambda = \lambda_Z = \lambda_\gamma$ .

## 2 Combined Final States

The TGC limits presented here are derived combining previously published measurements in four diboson final states:  $W\gamma \rightarrow \ell\nu\gamma$ ,  $WW/WZ \rightarrow \ell\nu jj$ ,  $WW \rightarrow \ell\nu\ell'\nu$ , and  $WZ \rightarrow \ell\nu\ell'\bar{\ell}'$  [4]. The process  $W\gamma \rightarrow \ell\nu\gamma$  is sensitive to the  $WW\gamma$  coupling. The  $0.7 \text{ fb}^{-1}$  of data were analyzed to select events with an electron (muon) with  $E_T > 25 \text{ GeV}$  ( $20 \text{ GeV}$ ),  $\cancel{E}_T > 25$  ( $20$ )  $\text{GeV}$  and a photon with  $E_T^\gamma > 9 \text{ GeV}$ . It is required that the photon and lepton are separated in space of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$ . The final state radiation is suppressed requiring the transverse mass of the lepton, photon, and  $\cancel{E}_T$  to be  $> 120$  ( $110$ )  $\text{GeV}$ . In total 263 candidate events are observed. After subtracting backgrounds, the signal is measured to be  $187 \pm 17_{\text{stat}} \pm 4_{\text{sys}}$  events and is consistent with the SM prediction of  $197 \pm 15$  events. The photon spectra are input for the combination. For  $W\gamma$  production in presence of anomalous TGCs, spectra were simulated using the Baur Monte Carlo (MC) event generator [5].

The  $WW/WZ \rightarrow \ell\nu jj$  analysis probes both the  $ZWW$  and  $\gamma WW$  vertex. We analyze  $1.07 \text{ fb}^{-1}$  of data selecting events with a lepton of  $p_T > 20 \text{ GeV}$ ,  $\cancel{E}_T > 20 \text{ GeV}$ , and at least two jets with  $p_T > 20 \text{ GeV}$  with the leading jet of  $p_T > 30 \text{ GeV}$ . In total 26865 candidate events are observed which is consistent with the SM prediction of  $26830 \pm 828$  events. The dijet  $p_T$  spectrum is used as input for the combination. Spectra with anomalous TGCs are generated by re-weighting the PYTHIA MC SM spectra to match spectra generated by a LO MC from Hagiwara, Zeppenfeld, and Woodside (HZW) [3].

The  $WW \rightarrow \ell\nu\ell'\nu$  analysis uses  $1 \text{ fb}^{-1}$  of data. For all channels ( $ee$ ,  $e\mu$ , and  $\mu\mu$ ), the leading lepton must satisfy  $p_T > 25 \text{ GeV}$  and the trailing lepton with  $p_T > 15 \text{ GeV}$ . Both leptons must be of opposite charge. In the data 100 candidate events are observed, which is consistent with the prediction of  $102.9 \pm 4.4$  events. Two-dimensional histograms of leading and trailing lepton  $p_T$  are used as input in the combination. Histograms are generated using the HZW MC.

Analysis of  $WZ \rightarrow \ell\nu\ell'\bar{\ell}'$  final states uses  $1 \text{ fb}^{-1}$  of data. Four final states ( $eee$ ,  $ee\mu$ ,  $\mu\mu e$ , and  $\mu\mu\mu$ ), require three leptons with  $p_T > 15 \text{ GeV}$  and  $\cancel{E}_T > 20 \text{ GeV}$ . To select  $Z$  candidates, like-flavor leptons must satisfy  $71 < m_{ee} < 111 \text{ GeV}$  or  $50 < m_{\mu\mu} < 130 \text{ GeV}$ . To reduce  $t\bar{t}$  background events the magnitude of the vector sum of the charged lepton  $p_T$  and the  $\cancel{E}_T$  must be less than  $50 \text{ GeV}$ . The sum over all channels yields 13 candidate events which is in agreement with the SM prediction of  $13.7 \pm 1.2$  events. The  $p_T^Z$  of the  $Z$  boson is used in the combination and simulated using the HZW MC.

## 3 Results

The one-dimensional 68% and 95% C.L. limits for each coupling are shown in Table 1 for two scenarios. The measured values and the one-dimensional 68% C.L. intervals of the  $W$  boson magnetic dipole and electric quadrupole moments for  $SU(2)_L \times U(1)_Y$  scenario (with  $g_1^Z = 1$ ) are  $\mu_W = 2.02_{-0.09}^{+0.08} (e/2M_W)$  and  $q_W = -1.00 \pm 0.09 (e/M_W^2)$ , respectively. Two-dimensional surfaces in  $q_W - \mu_W$  space for both scenarios are shown in Figure 1.

## 4 Summary

Presented results are the most stringent limits on anomalous values of  $\gamma WW$  and  $WWZ$  TGCs measured from hadronic collisions to date. The 95% C.L limits in both scenarios improve relative to the previous combined DØ [6] and CDF [7] results by a factor of  $\sim 3$ . Our measurements

| Par.I                 | Min. | 68% C.L.    | 95% C.L.    | Par.II         | Min. | 68% C.L.    | 95% C.L.    |
|-----------------------|------|-------------|-------------|----------------|------|-------------|-------------|
| $\Delta\kappa_\gamma$ | 0.07 | -0.13, 0.23 | -0.29, 0.38 | $\Delta\kappa$ | 0.03 | -0.04, 0.11 | -0.11, 0.18 |
| $\Delta g_1^Z$        | 0.05 | -0.01, 0.11 | -0.07, 0.16 |                |      |             |             |
| $\lambda$             | 0.00 | -0.04, 0.05 | -0.08, 0.08 | $\lambda$      | 0.00 | -0.05, 0.05 | -0.08, 0.08 |

Table 1: One-dimensional minimum and combined 68% and 95% C.L. limits on anomalous  $\gamma/ZWW$  couplings for two scenarios:  $SU(2)_L \times U(1)_Y$  (Par.I) and equal couplings (Par.II), both with  $\Lambda_{NP} = 2$  TeV.

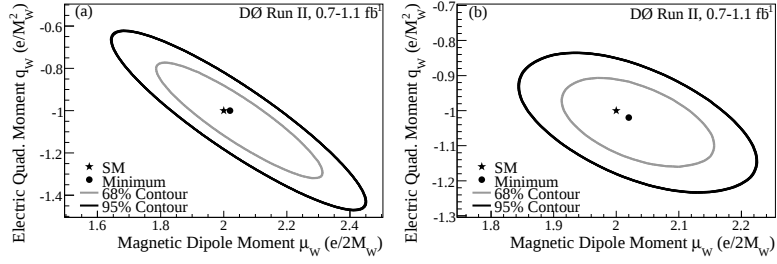


Figure 1: Two-dimensional 68% and 95% C.L. limits for the  $W$  boson electric quadrupole moment versus the magnetic dipole moment for (a)  $SU(2)_L \times U(1)_Y$  scenario and (b) equal couplings scenario ( $\Lambda_{NP} = 2$  TeV in both scenarios).

are comparable to that of an individual LEP2 experiments [8] even though all four analyses considered in this combination are limited by statistics. The DØ experiment also sets the most stringent measurements of  $\mu_W$  and  $q_W$  moments to date.

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