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 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 $g_V^V = \kappa_V = 1$ ($V = \gamma/Z$). The value of $g_\gamma^V$ is fixed by electromagnetic (EM) gauge invariance ($g_\gamma^V = 1$) while the value of $g_Z^V$ 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: $\Delta \kappa_\gamma$, $\Delta g_Z^V$, $\Delta \kappa_Z$, $\lambda_\gamma$ and $\lambda_Z$. Couplings $g_V^V$, $\kappa_\gamma$ and $\lambda_\gamma$ also relate to the $W$ boson magnetic dipole moment $\mu_W$ and electromagnetic quadrupole moment $q_W$ as $\mu_W = \frac{e}{M_W} (g_V^V + \kappa_\gamma + \lambda_\gamma)$ and $q_W = -\frac{e}{M_W} (\kappa_\gamma - \lambda_\gamma)$.

Anomalous TGCs could cause an unphysical increase in diboson production cross sections as the center-of-mass energy, $\sqrt{s}$, 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 $\hat{s} \to \infty$. 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 $\Delta \kappa_\gamma$, $\Delta g_V^V$ and $\lambda$ couplings: $\Delta \kappa_Z = \Delta g_V^V - \Delta \kappa_\gamma \cdot \tan^2 \theta_W$ 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 $\Delta g_V^V$.

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, $\Delta g_V^V = \Delta g_Z^V = 0$ and the relations between the couplings become: $\Delta \kappa = \Delta \kappa_Z = \Delta \kappa_\gamma$ and $\lambda = \lambda_Z = \lambda_\gamma$.  

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2 Combined Final States

The TGC limits presented here are derived combining previously published measurements in four diboson final states: \( W\gamma \rightarrow \ell\nu\gamma \), \( WW/Z\gamma \rightarrow \ell\nu jj \), \( WW \rightarrow \ell\nu\ell\nu \), and \( WZ \rightarrow \ell\nu\ell\nu \) [4]. The process \( W\gamma \rightarrow \ell\nu\gamma \) is sensitive to the \( WW\gamma \) coupling. The 0.7 fb\(^{-1}\) of data were analyzed to select events with an electron (muon) with \( E_T > 25 \text{ GeV} \) (20 GeV), \( E_T > 25 \) (20) 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 \( E_T \) to be > 120 (110) 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 \( WW/Z\gamma \rightarrow \ell\nu jj \) analysis probes both the \( ZWW \) and \( \gamma WW \) vertex. We analyze 1.07 fb\(^{-1}\) of data selecting events with a lepton of \( p_T > 20 \text{ GeV} \), \( E_T > 20 \text{ GeV} \), 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 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 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 \( WZ \rightarrow \ell\nu\ell\nu \) final states uses 1 fb\(^{-1}\) of data. Four final states (\( eee, e\mu\mu, \mu\mu\), and \( \mu\mu\mu \)), require three leptons with \( p_T > 15 \text{ GeV} \) and \( E_T > 20 \text{ GeV} \). To select \( Z \) candidates, like-flavor leptons must satisfy \( 71 < m_{ee} < 111 \operatorname{GeV} \) or \( 50 < m_{\mu\mu} < 130 \operatorname{GeV} \). To reduce \( t\bar{t} \) background events the magnitude of the vector sum of the charged lepton \( p_T \) and \( E_T \) must be less than 50 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 \( g^2 = 1 \)) 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 DO [6] and CDF [7] results by a factor of \( \sim 3 \). Our measurements
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.

<table>
<thead>
<tr>
<th></th>
<th>Min.</th>
<th>68% C.L.</th>
<th>95% C.L.</th>
<th></th>
<th>Min.</th>
<th>68% C.L.</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \kappa_{\gamma}$</td>
<td>0.07</td>
<td>-0.13, 0.23</td>
<td>-0.29, 0.38</td>
<td>$\Delta \kappa$</td>
<td>0.03</td>
<td>-0.04, 0.11</td>
<td>-0.11, 0.18</td>
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<tr>
<td>$\Delta g_{\tilde{\gamma}}^Z$</td>
<td>0.05</td>
<td>-0.01, 0.11</td>
<td>-0.07, 0.16</td>
<td>$\lambda$</td>
<td>0.00</td>
<td>-0.04, 0.05</td>
<td>-0.08, 0.08</td>
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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.

References