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Combined measurements of anomalous charged trilinear gauge-boson couplings from diboson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present measurements of the anomalous $WW\gamma$ and WWZ trilinear gauge couplings from a combination of four diboson production and decay channels using data collected by the D0 detector at the Fermilab Tevatron Collider. These results represent the first high statistics combination of limits across different diboson production processes at the Tevatron and use data corresponding to an integrated luminosity of approximately 1 fb^{-1}. When respecting $SU(2)_L \otimes U(1)_Y$ symmetry, we measure central values and 68% C.L. allowed intervals of $\kappa_\gamma = 1.07^{+0.16}_{-0.20}$, $\lambda = 0.00^{+0.05}_{-0.04}$ and $g_1^Z = 1.05 \pm 0.06$. We present the most stringent measurements to date for the W boson magnetic dipole and electromagnetic quadrupole moments of $\mu_W = 2.02^{+0.08}_{-0.09}\,(e/2M_W)$ and $q_W = -1.00 \pm 0.09\,(e/M_W^2)$, respectively.

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The gauge theory of electroweak interactions contains a striking feature. In quantum electrodynamics, the photons carry no electric charge and thus lack photon-to-photon couplings and do not self-interact. In contrast, the weak vector bosons carry weak charge and do interact amongst themselves through trilinear and quartic gauge boson vertices.

The most general $WW\gamma$ and WWZ interactions can be described [1, 2] using a Lorentz invariant effective Lagrangian that contains fourteen dimensionless couplings, seven each for $WW\gamma$ and WWZ. Assuming electromagnetic gauge invariance and CP conservation reduces the number of independent couplings to five (electromagnetic gauge invariance requires $g_1^\gamma = 1$), and the Lagrangian takes the form:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu V^{\nu\lambda}$$

where W^μ denotes the W boson field, $W_{\mu\nu}{=}\partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $V{=}\gamma$ or Z, and M_W is the mass of the W boson. The global coupling parameters g_{WWV} are $g_{WW\gamma}{=}{-}e$ and $g_{WWZ} = -e\cot\theta_W$, as in the standard model (SM) in which e and θ_W are the magnitude of the electron charge and the weak mixing angle, respectively. In the SM $\lambda_\gamma{=}\lambda_Z{=}0$ and $g_1^\gamma{=}g_1^Z{=}\kappa_\gamma{=}\kappa_Z{=}1$. For convenience, anomalous trilinear gauge couplings (anomalous TGCs) $\Delta\kappa_V$ and Δg_1^Z are defined as $\kappa_V - 1$ and $g_1^Z - 1$, respectively.

The W boson magnetic dipole μ_W and electric quadrupole q_W moments may be expressed in terms of the coupling parameters as

$$\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

$$q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

As mentioned above, $g_1^\gamma{=}1$.

If the coupling parameters have non-SM values then the amplitudes for gauge boson pair production grow with energy, eventually violating tree-level unitarity. The unitarity violation can be controlled by parametrizing the anomalous couplings as dipole form factors with a cutoff scale, Λ. The anomalous couplings then take a form $a(\hat{s}) = a_0/(1+\hat{s}/\Lambda^2)^2$ in which $\hat{s}$ is the center-of-mass energy of the colliding partons and a_0 is the coupling value in the limit $\hat{s} \to 0$ [3]. The quantity Λ is physically interpreted as the mass scale where the new phenomenon responsible for the anomalous couplings is directly observable. The cutoff Λ is conservatively set at the limit of sensitivity, close to the collision center-of-mass energy. We use $\Lambda = 2$ TeV; coupling limits depend only weakly on Λ for $\Lambda > 1$ TeV in hadronic collisions at Tevatron energies.

We measure the electroweak coupling parameters through the study of gauge boson pairs. Several processes contribute to SM boson pair production. Fig. 1(a) shows t-channel production of dibosons in which V_1V_2 are WW, WZ, or $W\gamma$. The s-channel production shown in Fig. 1(b) involves boson self-interactions through a trilinear gauge vertex. Final states (V_1V_2) produced via the WWZ coupling are WW or WZ. Final states produced through the $WW\gamma$ coupling are WW or $W\gamma$. The typical effect of anomalous TGCs is to increase the cross section especially at high boson transverse momentum (p_T). We thus analyze corresponding observables to measure such effects.

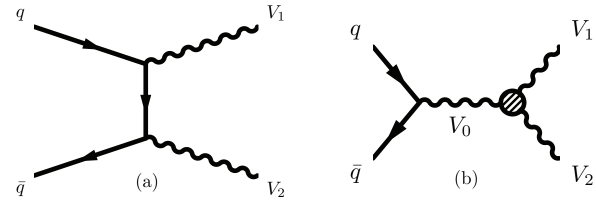

FIG. 1: Vector boson pair production via (a) t-channel and (b) s-channel diagrams. For $V_1 = W$ and $V_2 = \gamma/Z$, $V_0 = W$. For $V_1 = V_2 = W$, $V_0 = \gamma/Z$.

Previously published limits on anomalous TGCs from a combination of channels come from the D0 Collaboration in the 1992-1996 Tevatron run with integrated luminosity ($\mathcal{L}$) of 100 pb^{-1} [4], the CDF Collaboration with the current Tevatron run ($\mathcal{L}{\sim}350$ pb^{-1}) [5], and LEP2 experiments [6]. The best previously published W boson magnetic dipole moment result is from a combination of measurements by the DELPHI Collaboration [7].

In this paper, we investigate the $WW\gamma$ and WWZ trilinear vertices through diboson production. We set limits on the non-SM or anomalous TGC parameters λ_V, $\Delta\kappa_V$, and Δg_1^Z. These limits are derived from a combination of previously published measurements involving four final states: $W\gamma{\to}\ell\nu\gamma$, $WW/WZ{\to}\ell\nu jj$, $WW{\to}\ell\nu\ell'\nu$, and $WZ{\to}\ell\nu\ell'\bar{\ell}'$, in which ℓ is an electron or muon, ν is a neutrino, and j is a jet. Each measurement used data collected by the D0 detector [8] from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV delivered by the Fermilab Tevatron Collider.

The process $W\gamma{\to}\ell\nu\gamma$ is sensitive only to the $WW\gamma$ coupling. The process was studied with data corresponding to 0.7 fb^{-1} [9]. The main requirements were an electron with transverse energy $E_T{>}25$ GeV or a muon with transverse momentum $p_T{>}20$ GeV, a photon with $E_T{>}9$ GeV, missing transverse energy $\not\!\!E_T{>}25$ (20) GeV for the electron (muon) channel, and separation between the photon and lepton in $\eta{-}\phi$ [10] space of $\Delta R{=}\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}{>}0.7$. Furthermore, to suppress final state radiation the three-body transverse mass [11] of the lepton, photon, and $\not\!\!E_T$ was required to exceed 120 (110) GeV for the electron (muon) channel. In total 180 (83) candidate $e\nu\gamma$ ($\mu\nu\gamma$) events were observed. After subtracting backgrounds, the signal was $130 \pm 14_{\rm stat} \pm 3.4_{\rm syst}$ (57±8.8±1.8) events, consistent with the SM prediction of 120±12 (77±9.4) events for the $e\nu\gamma$ ($\mu\nu\gamma$) channel. The photon E_T spectra of the $W\gamma$ candidates in the data and those estimated for the backgrounds are input into the combination. For $W\gamma$ production in the presence of TGCs, spectra were simulated using the Baur Monte Carlo (MC) [12, 13] with a fine grid in $\lambda_\gamma{-}\Delta\kappa_\gamma$ space.

The $WW\to\ell\nu\ell'\nu$ measurement [14] used data corresponding to an integrated luminosity of 1 fb^{-1}. The data were divided into three channels defined by the flavor of the leptons from the W boson decays: ee, $e\mu$, and $\mu\mu$. For all channels, the leading lepton had p_T>25 GeV and the trailing lepton had p_T>15 GeV. The leptons were required to have opposite charge. In the data 22 (ee), 64 ($e\mu$) and 14 ($\mu\mu$) candidate events were observed, consistent with the sum of SM WW and backgrounds of 23.5±1.9 (ee), 68.6±3.9 ($e\mu$) and 10.8±0.6 ($\mu\mu$) events. Two-dimensional histograms of leading and trailing lepton p_T were produced for the data and backgrounds and used as inputs in the combination. Distributions for SM and anomalous TGC values were generated using the WW/WZ event generator from Hagiwara, Zeppenfeld, and Woodside (HZW) [2].

The $WZ\to\ell\nu\ell'\bar{\ell}'$ measurement [15] selected the four final states eee, $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$. The data corresponded to an integrated luminosity of 1 fb^{-1}. All three charged leptons were required to have p_T>15 GeV. Z boson candidates consisted of like-flavor lepton pairs with mass 71<M_{ee}<111 GeV or 50<$M_{\mu\mu}$<130 GeV. For the eee and $\mu\mu\mu$ channels, the oppositely charged lepton pair with mass closest to the Z pole mass was chosen as the Z boson candidate. To select W boson candidates, the $\not\!\!E_T$ must have exceeded 20 GeV. To reduce background events from $t\bar{t}$ to a negligible level, the magnitude of the vector sum of the charged lepton transverse momenta and the $\not\!\!E_T$ was required to be less than 50 GeV. The sum over all channels yielded 13 candidate events in the data consistent with a SM estimate of 9.2 ± 1.0 WZ events and 4.5 ± 0.6 background events. The p_T of the Z boson is sensitive to anomalous TGCs and is used in the combination. The HZW MC is used to estimate the SM spectrum as well as spectra from anomalous TGCs.

Finally, the $WW/WZ\to\ell\nu jj$ measurement [16] selected events in which one W boson decays leptonically and the other boson decays hadronically. The data corresponded to an integrated luminosity of 1.1 fb^{-1}. The main requirements were an electron or muon with p_T>20 GeV, $\not\!\!E_T$>20 GeV, and at least two jets with p_T>20 GeV with the leading jet satisfying p_T>30 GeV. In total 12,473 (14,392) candidate events in the $e\nu jj$ ($\mu\nu jj$) channel were observed, consistent with the SM prediction of 12,460±550 (14,370±620) $e\nu jj$ ($\mu\nu jj$) events [17]. An observable sensitive to anomalous TGCs is the p_T of the dijet system. The data and background spectra for this variable are used as inputs for the combination. Spectra with anomalous TGCs were generated with the HZW MC.

Distributions of the sensitive observables mentioned above for each final state are generated for signal with the corresponding Monte Carlos and for backgrounds using simulations or data. The signal distributions vary as a function of the TGC parameters under study both in spectral shape and event yield. In addition to allowing variation in the TGC parameters themselves, nuisance parameters are used to allow systematic offsets to vary within their uncertainties. A simultaneous fit to the data distributions is performed in order to determine the anomalous TGC limits. The χ^2 function used in this fit is [18]:

$$\begin{aligned}\chi^2 &= -2\ln\left(\prod_{i=1}^{N_b}\frac{\mathcal{L}^P(d_i;m_i(\vec{R}))}{\mathcal{L}^P(d_i;d_i)}\prod_{k=1}^{N_s}\frac{\mathcal{L}^G(R_k\sigma_k;0,\sigma_k)}{\mathcal{L}^G(0;0,\sigma_k)}\right)\\ &= 2\sum_{i=1}^{N_b} m_i(\vec{R}) - d_i - d_i\ln\left(\frac{m_i(\vec{R})}{d_i}\right) + \sum_{k=1}^{N_s} R_k^2, \quad (1)\end{aligned}$$

in which the variables i and k index the number of histogram bins (N_b) and the number of systematic uncertainties (N_s) respectively. In this function $\mathcal{L}^P(\alpha;\beta)$ is the Poisson probability for α events with a mean of β events; $\mathcal{L}^G(x;\mu,\sigma)$ is the Gaussian probability for the value x in a distribution with a mean value of μ and a variance σ^2; R_k (in vector form as $\vec{R}$) is a dimensionless parameter describing departures in nuisance parameters in units of the associated systematic uncertainty σ_k; d_i is the number of data events in bin i; and $m_i(\vec{R})$ is the number of predicted events in bin i. The number of bins used in the fit is the sum of the number of bins in each kinematic distribution for each channel.

In total 49 sources of systematic uncertainty are considered. As implied in Eq. 1, systematic uncertainties are treated as Gaussian priors on the expected number(s) of events. Systematic uncertainties on the luminosity, lepton identification, and theoretical uncertainties on the cross sections for the backgrounds estimated from MC are correlated across all observables. Uncertainties on background estimates based on data are correlated across specific final states within a diboson production channel as appropriate. The uncertainties with the largest impact on the result are those related to background cross sections and the luminosity. The effect of incorporating systematic uncertainties into the fit is to degrade the resulting limits by ∼30%.

Four two-dimensional surfaces in TGC space are examined: (a) each of the three pairings of the three free parameters ($\Delta\kappa_\gamma$, λ, Δg_1^Z) while respecting $SU(2)_L\otimes U(1)_Y$ symmetry by using the constraints $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma = \lambda$ [19] and (b) the $(\Delta\kappa, \lambda)$ plane for the equal-couplings scenario [2] in which $\kappa_\gamma = \kappa_Z = \kappa$, $\lambda_\gamma = \lambda_Z = \lambda$. The two-dimensional 68% and 95% C.L. contours are shown in Figs. 2 and 3. The two-dimensional contours for W boson magnetic dipole and electric quadrupole moments are shown in Fig. 4. The one-dimensional 68% and 95% C.L. limits for each coupling parameter, with the other couplings parameters fixed at their SM values, are shown in Table I.

These results provide the most stringent limits on anomalous values of $WW\gamma$ and WWZ TGCs measured from hadronic collisions to date. The 95% C.L. limits in both scenarios represent an improvement relative to the previous D0 [4] and CDF [5] results of about a factor of 3. When respecting $SU(2)_L \otimes U(1)_Y$ symme-

TABLE I: One-dimensional χ^2 minimum and 68% and 95% C.L. allowed intervals on anomalous values of $WW\gamma$ and WWZ TGCs. Note that μ_W and q_W are in units of $(e/2M_W)$ and (e/M_W^2) respectively.

Results respecting $SU(2)_L \otimes U(1)_Y$ symmetry			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$[-0.13, 0.23]$	$[-0.29, 0.38]$
Δg_1^Z	0.05	$[-0.01, 0.11]$	$[-0.07, 0.16]$
λ	0.00	$[-0.04, 0.05]$	$[-0.08, 0.08]$
μ_W	2.02	$[1.93, 2.10]$	$[1.86, 2.16]$
q_W	-1.00	$[-1.09, -0.91]$	$[-1.16, -0.84]$
Results for equal-couplings			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa$	0.03	$[-0.04, 0.11]$	$[-0.11, 0.18]$
λ	0.00	$[-0.05, 0.05]$	$[-0.08, 0.08]$
μ_W	2.02	$[1.94, 2.09]$	$[1.88, 2.15]$
q_W	-1.02	$[-1.09, -0.94]$	$[-1.16, -0.87]$

try, our measurements with 68% C.L. allowed intervals of $\kappa_\gamma = 1.07^{+0.16}_{-0.20}$, $\lambda = 0.00^{+0.05}_{-0.04}$ and $g_1^Z = 1.05^{+0.06}_{-0.06}$ are only factors of approximately $2-3$ times less sensitive than the combined results from the four LEP2 experiments: $\kappa_\gamma = 0.973^{+0.044}_{-0.045}$, $\lambda = -0.028^{+0.020}_{-0.021}$ and $g_1^Z = 0.984^{+0.022}_{-0.019}$, also at 68% C.L. [6]. Furthermore, with only 1 fb^{-1} of data our sensitivity is comparable to that of an individual LEP2 experiment [7, 20–22].

We also extract measurements of the W boson magnetic dipole and electric quadrupole moments. When respecting $SU(2)_L \otimes U(1)_Y$ symmetry with g_1^Z=1 we measure 68% C.L. intervals (one-dimensional with the other parameter held at its SM value) of $\mu_W = 2.02^{+0.08}_{-0.09}\,(e/2M_W)$ and $q_W = -1.00 \pm 0.09\,(e/M_W^2)$, respectively. The most stringent previously published result is $\mu_W = 2.22^{+0.20}_{-0.19}\,(e/2M_W)$ and $q_W = -1.18^{+0.27}_{-0.26}\,(e/M_W^2)$ from the DELPHI Collaboration [7].

In summary, we presented measurements of anomalous $WW\gamma$ and WWZ trilinear gauge couplings and related W boson magnetic dipole and electric quadrupole moments based on the combination of four diboson production and decay channels using 0.7−1.1 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron Collider. Currently, all measurements considered in this combination are limited by statistics. A combination of CDF and D0 data with 5 fb^{-1} each will reduce the statistical uncertainty by a factor of three to levels comparable or better than the combined LEP2 limits.

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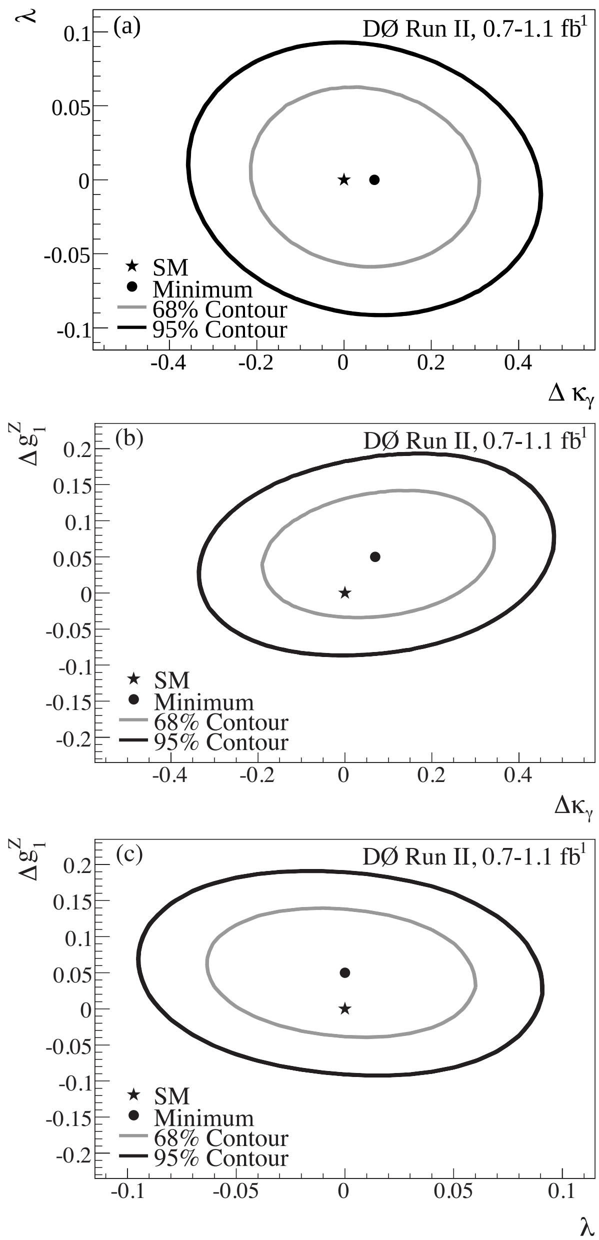

FIG. 2: Two-dimensional 68% and 95% C.L. limits when respecting $SU(2)_L \otimes U(1)_Y$ symmetry and assuming $\Lambda = 2$ TeV, for (a) λ vs. $\Delta\kappa_\gamma$, (b) Δg_1^Z vs. $\Delta\kappa_\gamma$, and (c) Δg_1^Z vs. λ. In each case, the third coupling is set to its SM value.

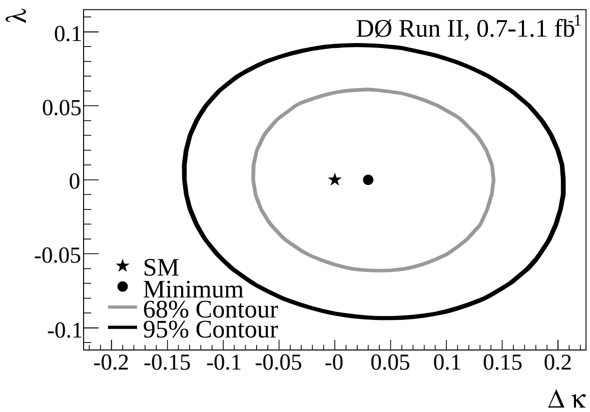

FIG. 3: Two-dimensional 68% and 95% C.L. limits for λ vs. $\Delta\kappa$ when enforcing the equal-couplings constraints and assuming $\Lambda = 2$ TeV.

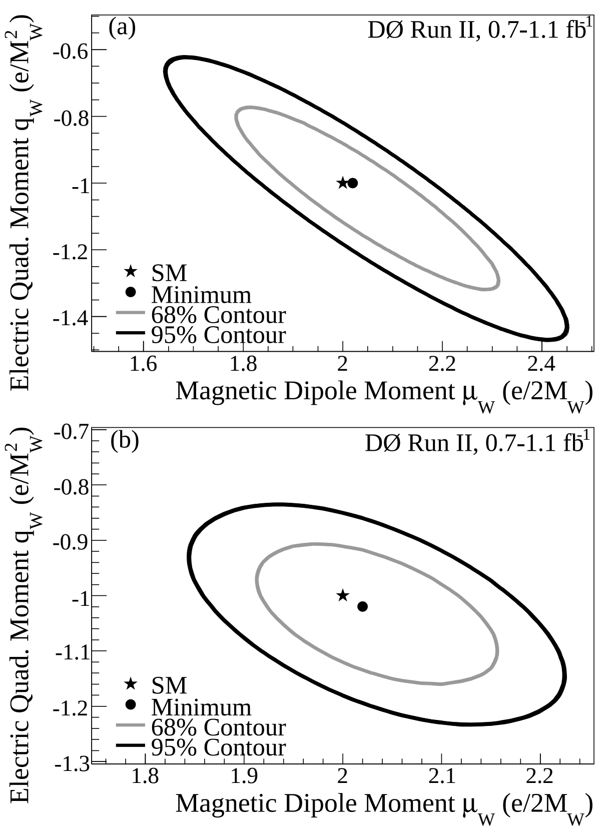

FIG. 4: Two-dimensional 68% and 95% C.L. limits for the W boson electric quadrupole moment vs. the magnetic dipole moment (a) when respecting $SU(2)_L \otimes U(1)_Y$ symmetry and (b) when enforcing equal-couplings constraints. In both cases we assume $\Lambda = 2$ TeV.