Measurement of trilinear gauge boson couplings from \(WW + WZ \to \ell \nu jj\) events in \(p\bar{p}\) collisions at \(\sqrt{s} = 1.96\) TeV

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We present a direct measurement of trilinear gauge boson couplings at $\gamma WW$ and $ZW W$ vertices in $WW$ and $WZ$ events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We consider events with one electron or muon, missing transverse energy, and at least two jets. The data were collected using the D0 detector and correspond to 1.1 fb$^{-1}$ of integrated luminosity. Considering two different relations between the couplings at the $\gamma WW$ and $ZW W$ vertices, we measure these couplings at 68% C.L. to be $\kappa_1 = 1.07_{-0.29}^{+0.26}$, $\lambda = 0.06_{-0.06}^{+0.06}$, and $g_{L}^{Z} = 1.04_{-0.09}^{+0.09}$ in a scenario respecting $SU(2)_L \otimes U(1)_Y$ gauge symmetry and $\kappa = 1.04_{-0.11}^{+0.11}$ and $\lambda = 0.00_{-0.06}^{+0.06}$ in an “equal couplings” scenario.

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I. INTRODUCTION

A primary motivation for studying diboson physics is that the production of two weak bosons and their interactions provide tests of the electroweak sector of the standard model (SM) arising from the vertices involving trilinear gauge boson couplings (TGCs) [1]. Any deviation of TGCs from their predicted SM values would be an indication for new physics [2] and could provide information on a mechanism for electroweak symmetry breaking (EWSB).

The TGCs involving the $W$ boson have been previously probed in $WW$, $W\gamma$, and $WZ$ production at the Tevatron $p\bar{p}$ Collider [3–10] and $WW$ production at the CERN $e^+e^-$ collider (LEP) [8,9,10], at different center-of-mass energies and luminosities but no devia-
tion from the SM predictions has been observed. The LEP experiments benefit from the full reconstruction of event kinematics in $e^+e^-$ collisions, high signal selection efficiencies and small background contamination. At the Tevatron, despite larger backgrounds and limited ability to fully reconstruct event kinematics, larger collision energies are probed and $WZ$ production can be used to directly probe the $ZWW$ coupling. The study of $WW$ and $WZ$ production at hadron colliders has focused primarily on the purely leptonic final states \[3,4,11\]. In this paper we present a measurement of the $\gamma WW/ZWW$ couplings based on the same dataset used to obtain the recent evidence for semileptonic decays of $WW/WZ$ boson pairs in hadron collisions \[12\].

As shown in the tree-level diagrams of Fig. 1, TGCs contribute to $WW/WZ$ production via $s$-channel diagrams. Production of $WW$ via the $s$-channel process contains both trilinear $\gamma WW$ and $ZWW$ gauge boson vertices. On the other hand, $WZ$ production is sensitive exclusively to the $ZWW$ vertex.

In a Higgs-less scenario or for heavier Higgs boson masses this unitarity limit on the Higgs boson mass indicates the mass scale at which the SM must be superseded by new physics in order to restore unitarity at TeV energies. In this case, the SM is considered to be a low-energy approximation of a general theory. Conversely, if a light Higgs boson exists, the SM may nevertheless be incomplete and new physics could appear at higher energies.

The effects of this general theory can be described by an effective Lagrangian, $\mathcal{L}_{\text{eff}}$, describing low-energy interactions of the new physics at higher energies in a model-independent manner. Expanding in powers of $(1/\Lambda_{NP})$ \[14\]:

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{SM} + \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]

where $\mathcal{L}_{\text{eff}}^{SM}$ is the $SU(2)_L \times U(1)_Y$ gauge-invariant SM Lagrangian, $\Lambda_{NP}$ is the energy scale of the new physics and $i$ sums over all operators $\mathcal{O}_i$ of the given energy dimension $(n + 4)$. The coefficients $f_i$ parametrize all possible interactions at low energies. Effects of the new physics may not be directly observable because the scale of the new physics is above the energies currently experimentally accessible. However, there could be indirect consequences with measurable effects; for example, on gauge boson interactions.

For the study of gauge boson interactions, the relevant terms in Eq. (1) are those that produce vertices with three or four gauge bosons. The effective Lagrangian, $\mathcal{L}_{\text{eff}}$, that parametrizes the most general Lorentz invariant $VWW$ vertices ($V = Z, \gamma$) involving two $W$ bosons can be defined as \[13\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = ig_Y^1 (W^\mu_{\mu\nu} W^{\mu\nu} - W^{\mu\nu} W^\nu_{\mu\nu}) + ig_Y^2 W^\mu_{\mu\nu} W^{\mu\nu} + i \frac{g_Y^3}{M_W} W^\mu_{\lambda \nu} W^\nu_{\mu \lambda} - g_Y^4 W^\mu_{\mu\nu} (\partial^\mu V^{\nu\rho} + \partial^\nu V^{\mu\rho}) + g_Y^5 \epsilon^{\mu\nu\lambda\rho} (W^\mu_{\nu\rho} \partial_\lambda V^\rho - \partial_\rho W^\nu_{\mu\rho} V^\rho) + i g_Y^6 W^\mu_{\mu\nu} V^{\nu\rho} + i \frac{\Lambda_{NP}}{M_W} W^\mu_{\lambda \nu} W^\nu_{\mu \lambda} \epsilon^{\mu\nu\lambda\rho}
\tag{2}
\]

where $\epsilon_{\mu\nu\lambda\rho}$ is the fully antisymmetric $\epsilon$ tensor, $W$ denotes the $W$ boson field, $V$ denotes the photon or Z boson field, $V^{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $W^{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $\epsilon^{\mu\nu\lambda\rho} = 1/2(\epsilon_{\mu\nu\lambda\rho} V^{\lambda\rho})$, $g_{\gamma WW} = -e$, and $g_{ZW} = -e \cot \theta_W$, where $e$ is the electron electric charge, $\theta_W$ is the weak mixing angle and $M_W$ is the $W$ boson mass. The 14 coupling parameters of $VWW$ vertices are grouped according to the symmetry properties of their corresponding operators: $C$ (charge conjugation) and $P$ (parity) conserving ($g_Y^1$, $\kappa_V$, and $\lambda_V$), $C$ and $P$ violating but $CP$ conserving ($g_Y^2$, $\kappa_Y$, and $\lambda_Y$), and $CP$ violating ($g_Y^3$, $\kappa_C$, and $\lambda_C$). In the SM all couplings vanish ($g_Y^1 = g_Y^2 = \kappa_V = \lambda_Y = \lambda_C = 0$) except $g_Y^3 = \kappa_C = \lambda_C = 1$. The value of $g_Y^3$ is fixed by electromagnetic gauge invariance ($g_Y^3 = 1$) while the value of $g_Y^2$ 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

\[
L_{\text{eff}}^{VWW}_{\gamma WW} = \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = ig_Y^1 (W^\mu_{\mu\nu} W^{\mu\nu} - W^{\mu\nu} W^\nu_{\mu\nu}) + ig_Y^2 W^\mu_{\mu\nu} W^{\mu\nu} + i \frac{g_Y^3}{M_W} W^\mu_{\lambda \nu} W^\nu_{\mu \lambda} - g_Y^4 W^\mu_{\mu\nu} (\partial^\mu V^{\nu\rho} + \partial^\nu V^{\mu\rho}) + g_Y^5 \epsilon^{\mu\nu\lambda\rho} (W^\mu_{\nu\rho} \partial_\lambda V^\rho - \partial_\rho W^\nu_{\mu\rho} V^\rho) + i g_Y^6 W^\mu_{\mu\nu} V^{\nu\rho} + i \frac{\Lambda_{NP}}{M_W} W^\mu_{\lambda \nu} W^\nu_{\mu \lambda} \epsilon^{\mu\nu\lambda\rho}
\tag{2}
\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]

\[
\mathcal{L}_{\text{eff}}^{VWW}_{\gamma WW} = \sum_{n \geq 1} \sum_i \frac{f_i}{\Lambda_{NP}^n} \mathcal{O}_i^{(n+4)} \tag{1}
\]
the anomalous TGCs \( \Delta g^Z_1 = (g^Z_1 - 1) \), \( \Delta \kappa_\gamma = (\kappa_\gamma - 1) \), \( \Delta \kappa_Z = (\kappa_Z - 1) \), \( \lambda_1 \), and \( \lambda_Z \).

If non zero anomalous TGCs are introduced in Eq. 2, an unphysical increase in the WW and WZ production cross sections will result as the center-of-mass energy, \( \sqrt{s} \), of the partonic constituents approaches \( \Lambda_{NP} \). Such divergences would violate unitarity, but can be controlled by introducing a form factor for which the anomalous coupling vanishes as \( \hat{s} \to \infty \):

\[
\Delta a(\hat{s}) = \frac{\Delta a_0}{(1 + \hat{s}/\Lambda_{NP}^2)^n} \tag{3}
\]

where \( n = 2 \) for \( \gamma WW \) and \( ZWW \) couplings, and \( a_0 \) is a low-energy approximation of the coupling \( a(\hat{s}) \).

Thus, the previously described anomalous TGCs scale as \( \Delta a_0 \) in Eq. 3. The values of \( \Delta a_0 \) (and \( a_0 \)) are constrained by requiring the \( S \)-matrix unitarity condition that bounds the \( J = 1 \) partial-wave amplitude of inelastic vector boson scattering by a constant. These constants were derived by Baur and Zeppenfeld 10 for each coupling that contributes to reduced helicity amplitudes in \( WZ \), \( \gamma W \), or WW production via \( s \)-channel. Calculated with \( M_H = 80 \text{ GeV} \), \( M_Z = 91.1 \text{ GeV} \) and with the dipole form factor as given by Eq. 3, the unitarity bounds for \( \Delta \kappa_\gamma \), \( \Delta \kappa_Z \), \( \Delta g^Z_1 \) and \( \lambda \) TGCs are

\[
|\Delta \kappa^0_\gamma| \leq \frac{n}{(n-1)^2} \times 1.81 \text{ TeV}^2, \quad |\Delta \lambda^0_\gamma| \leq \frac{n}{(n-1)^2} \times 0.96 \text{ TeV}^2
\]
\[
|\Delta \kappa^0_Z| \leq \frac{n}{(n-1)^2} \times 0.83 \text{ TeV}^2, \quad |\Delta \lambda^0_Z| \leq \frac{n}{(n-1)^2} \times 0.52 \text{ TeV}^2
\]
\[
|\Delta g^Z_1| \leq \frac{n}{(n-1)^2} \times 0.84 \text{ TeV}^2 \tag{4}
\]

For \( n = 2 \) and \( \Lambda_{NP} = 2 \text{ TeV} \), the unitarity condition sets constraints on the TGCs of \( |\Delta \kappa^0_\gamma| \leq 1.81, |\Delta \lambda^0_\gamma| \leq 0.96, |\Delta \kappa^0_Z| \leq 0.83, |\Delta \lambda^0_Z| \leq 0.52 \), and \( |\Delta g^Z_1| \leq 0.84 \). The scale of new physics, \( \Lambda_{NP} \), was chosen such that the unitarity limits are close to, but no tighter than, the coupling limits set by data. Clearly, as \( \Lambda_{NP} \) increases the effects on anomalous TGCs decrease and their observation requires either more precise measurements or higher \( \hat{s} \).

III. RELATIONS BETWEEN COUPLINGS

The interpretation of the effective Lagrangian [Eq. 1] depends on the specified symmetry and the particle content of the underlying low-energy theory. In general, \( \mathcal{L}_{\text{eff}} \) can be expressed using either the linear or nonlinear realization of the \( SU(2)_L \times U(1)_Y \) symmetry 17 to prevent unitarity violation, depending on its particle content. Thus, \( \mathcal{L}_{\text{eff}} \) can be rewritten in a form that includes the operators that describe interactions involving additional gauge bosons, and/or Goldstone bosons, and/or the Higgs field and operators of interest for any new physics effects. The number of operators can be reduced by considering their detectable contribution to the measured coupling.

Assuming the existence of a light Higgs boson, the low-energy spectrum is augmented by the Higgs doublet field \( \phi \), and \( SU(2)_L \) and \( U(1)_Y \) gauge fields. Because experimental evidence is consistent with the existence of an \( SU(2)_L \times U(1)_Y \) gauge symmetry, it is reasonable to require \( \mathcal{L}_{\text{eff}} \) to be invariant with respect to this symmetry. Thus, the second term in Eq. 1 consisting of operators up to energy dimension six, is also required to have local \( SU(2)_L \times U(1)_Y \) gauge symmetry and the underlying physics is described using a linear realization 18 of the \( SU(2)_L \times U(1)_Y \) gauge symmetry. By considering operators that give rise to nonstandard \( \gamma WW \) and \( ZWW \) couplings at the tree level, \( \mathcal{L}_{\text{eff}} \) can be parametrized in terms of the \( \alpha_i \) parameters 19. Those parameters relate to the \( f_i \) parameters of the Lagrangian given in Eq. 4 and to the TGCs in the Lagrangian of Eq. 2 as follows 20:

\[
\Delta \kappa_\gamma = (f_{\gamma \phi} + f_{B \phi}) \frac{M_W^2}{2 \Lambda_{NP}^2}, \quad \Delta g^Z_1 = \frac{g_{Z \gamma}^0}{\Lambda_{NP}}, \quad \Delta \kappa_Z = \frac{\alpha_{\kappa_\gamma}}{c_W^2}, \quad \Delta \gamma_W = \alpha_W, \quad \lambda = \lambda_\gamma = \Lambda_Z = \frac{3g^2}{2 \Lambda_{NP}} f_{WW} \tag{5}
\]

where \( g \) is the \( SU(2)_L \) gauge coupling constant \( (g = e/\sin \theta_W) \), \( c_W = \cos \theta_W \), \( s_W = \sin \theta_W \), and indices \( \lbrack \phi \rbrack \) and \( \lbrack \phi \rbrack \) refer to operators that describe the interactions between the \( W (B) \) gauge boson field and the Higgs field \( \phi \), and the gauge boson field interactions, respectively. The relations in Eq. 5 give the expected order of magnitude for TGCs to be \( O(M_W^2/\Lambda_{NP}^2) \). Thus, for \( \Lambda_{NP} \approx 2 \text{ TeV} \), the expected order of magnitude for \( \Delta \kappa_\gamma \), \( \Delta g^Z_1 \), and \( \lambda \) is \( O(10^{-3}) \). This gauge-invariant parametrization, also used at LEP, gives the following relations between the \( \Delta \kappa_\gamma \), \( \Delta g^Z_1 \) and \( \lambda \) couplings:

\[
\Delta \kappa_Z = \Delta g^Z_1 - \Delta \kappa_\gamma \cdot \tan^2 \theta_W \quad \text{and} \quad \lambda = \lambda_Z = \lambda_\gamma \tag{6}
\]

Hereafter we will refer to this relationship as the “LEP parametrization” [or \( SU(2) \times U(1) \) respecting scenario] with three different parameters: \( \Delta \kappa_\gamma \), \( \lambda \), and \( \Delta g^Z_1 \). The coupling \( \Delta \kappa_Z \) can be expressed via the relation given by Eq. 6.

A second interpretive scenario, referred to as the equal couplings (or \( ZWW=\gamma WW \) scenario) 11, specifies the \( \gamma WW \) and \( ZWW \) couplings to be equal. This is also relevant for studying interference effects between the photon and \( Z \)-exchange diagrams in \( WW \) production (see Fig. 1). In this case, electromagnetic gauge invariance forbids any deviation of \( g^Z_1 \) from its SM value \( (\Delta g^Z_1 = \Delta g^Z_1 = 0) \) and the relations between the couplings become

\[
\Delta \kappa \equiv \Delta \kappa_Z = \Delta \kappa_\gamma \quad \text{and} \quad \lambda \equiv \lambda_Z = \lambda_\gamma \tag{7}
\]

As already stated, for \( WW \) and \( WZ \) production the anomalous couplings contribute to the total cross section via the \( s \)-channel diagram. Anomalous couplings enter the differential production cross sections through different helicity amplitudes that depend on \( \hat{s} \). The coupling
The analyzed data were produced in relations between Eq. 6 and Eq. 7. Consequently, for a given $\hat{s}$, the sensitivity to the coupling $\lambda$ is higher than to $\kappa$ because $\lambda$ is multiplied by $\hat{s}$ in dominating amplitudes for $WW$ and $WZ$ production. Different sensitivity to the $\kappa$ couplings is expected due to the choice of scenario: the sensitivity to the $\kappa$ coupling in the equal couplings scenario is higher than in the LEP parametrization scenario simply because of the different relations between Eq. (6) and Eq. (7).

IV. D0 DETECTOR

The analyzed data were produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the Tevatron collider at Fermilab and collected by the D0 detector during 2002 - 2006. They correspond to $1.07 \pm 0.07$ fb$^{-1}$ of integrated luminosity for each of the two lepton channels ($eeqq$ and $\mu\nu qq$).

The D0 detector is a general purpose collider detector consisting of a central tracking system, a calorimeter system, and an outer muon system. The central tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for a central fiber 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20.2 ± 2.5(stat) ± 3.6(syst) ± 1.2(lumi) pb, which is consistent with the NLO SM predicted cross section of \(\sigma(WW + WZ) = 16.1 ± 0.9 \text{ pb}\) [30].

TABLE I: Measured number of events for signal and each background after the combined fit (with total uncertainties determined from the fit) and the number observed in data.

| Events / 10 GeV | 1σ on syst. | Dijet Mass (GeV) |
|-----------------|-------------|------------------|
| Diboson signal  | 436 ± 36    | 10100 ± 500      |
| W+jets          | 387 ± 61    | 436 ± 57         |
| Z+jets          | 1100 ± 200  | 1180 ± 180       |
| tt + single top | 426 ± 54    | 1180 ± 180       |
| Multijet        | 328 ± 83    | 328 ± 83         |
| Total predicted | 12460 ± 550 | 14370 ± 620      |
| Data            | 12473       | 14392            |

VI. SENSITIVITY TO ANOMALOUS COUPLINGS

For TGCs analysis we use the same selection and set limits on anomalous TGCs using a kinematic variable that is highly sensitive to the effects of deviations of \(\Delta\kappa, \lambda\), and \(\Delta g_1^Z\). Because TGCs introduce terms in the Lagrangian that are proportional to the momentum of the weak boson, the differential and the total cross sections will deviate from the SM prediction in the presence of anomalous couplings. This behavior is also expected at large production angles of a weak boson. Thus, the weak boson transverse momentum spectrum, \(p_T\), is sensitive to anomalous couplings and can show a significant enhancement at high values of \(p_T\).

The predicted \(WW\) and \(WZ\) production cross sections in the presence of anomalous TGCs are generated with the leading order (LO) MC generator of Hagiwara, Zeppenfeld, and Woodside (HZW) [1] with CTEQ5L [31] parton distribution functions (PDFs). For example, the predicted “anomalous” cross sections relative to the SM value given by the HZW generator are shown in Fig. 2 as a function of anomalous couplings. For this figure we vary only the \(\Delta\kappa\) coupling with the constraint between \(\Delta\kappa\) and \(\Delta\kappa_Z\) as given by Eq. 6. The couplings \(\lambda\) and \(\Delta g_1^Z\) are fixed to their SM values (i.e., \(\lambda = \Delta g_1^Z = 0\)). The effects of anomalous couplings on two WW kinematic distributions (\(p_T\) and rapidity of the \(q\bar{q}\) system) for the LEP parametrization are shown in Fig. 4. Here again, we vary only one coupling at a time (\(\Delta\kappa\), \(\lambda\), or \(\Delta g_1^Z\)) according to Eq. 6 and leave the others fixed to their SM values. Finally, we choose the \(p_T^2\) (i.e., reconstructed di-jet \(p_T\)) distribution to be our kinematic variable to probe anomalous couplings in data. Results are interpreted in two different scenarios: LEP parametrization and equal couplings, both with \(\Lambda_{NP} = 2\) TeV.

VII. REWEIGHTING METHOD

The Pythia [32] LO MC generator with CTEQ6L1 PDFs was used to simulate a sample of WW and WZ events at LO. We use the mc@nlo MC generator [33] with CTEQ6M PDFs to correct the event kinematics for higher order QCD effects by reweighting the differential distributions of \(p_T(WV)\) and \(\Delta R(WV)\) produced by Pythia to match those produced via mc@nlo. We simulate the LO effects of anomalous couplings on the \(p_T\) distribution by reweighting the SM predictions for WW and WZ production from Pythia to include the contribution from the presence of anomalous couplings. The anomalous coupling contribution to the normalization and to the shape of \(p_T^2\) distribution relative to the SM is predicted by the HZW LO MC generator.

The reweighting method uses the matrix element values given by the generator to predict an event rate in the presence of anomalous couplings. More precisely, an event rate \((R)\) is assigned representing the ratio of the differential cross section with anomalous couplings to the SM differential cross section. Because the HZW generator does not recalculate matrix element values, we use high statistics samples to estimate the weight as a function of different anomalous couplings. Thus, we consider our approach to be a close approximation of an exact reweighting method.

The basis of the reweighting method is that, in general, the equation of the differential cross section, which has a quadratic dependence on the anomalous couplings, can be written as

\[
d\sigma = \text{const} \cdot |M|^2 dX
\]

\[
= \text{const} \cdot |M_{\text{SM}}^2|^2 |M|^2 dX
\]

\[
= \text{const} \cdot |M_{\text{SM}}^2|^2 \begin{bmatrix} A(X)\Delta\kappa + B(X)\Delta\kappa^2 \\ C(X)\lambda + D(X)\lambda^2 + E(X)\Delta\kappa\lambda + \ldots \end{bmatrix} dX
\]

\[
= d\sigma_{\text{SM}} \cdot R(X; \Delta\kappa, \lambda, \ldots)
\]
where $d\sigma$ is the differential cross section that includes the contribution from the anomalous couplings, $d\sigma_{SM}$ is the SM differential cross section, $X$ is a kinematic distribution sensitive to the anomalous couplings and $A(X)$, $B(X)$, $C(X)$, $D(X)$, and $E(X)$ are reweighting coefficients dependent on $X$.

In the LEP parametrization, Eq. 8 is parametrized with the three couplings $\Delta \kappa_1$, $\lambda$, and $\Delta g_1^2$ and nine reweighting coefficients, $A(X) - I(X)$. Thus, the weight $R$ in the LEP parametrization scenario is defined as

$$ R \ (X; \Delta \kappa, \lambda, \Delta g_1) = 1 + A(X)\Delta \kappa + B(X)(\Delta \kappa)^2 + C(X)\lambda + D(X)\lambda^2 + E(X)\Delta \kappa \lambda $$

with $\Delta \kappa = \Delta \kappa_1$, $\lambda = \lambda_1$, and $\Delta g_1 = \Delta g_1^2$.

In the equal couplings scenario, Eq. 8 is parametrized with the two couplings $\Delta \kappa$ and $\lambda$ and five reweighting coefficients, $A(X) - E(X)$. In this case the weight is defined as

$$ R \ (X; \Delta \kappa, \lambda) = 1 + A(X)\Delta \kappa + B(X)\Delta \kappa^2 + C(X)\lambda + D(X)\lambda^2 + E(X)\Delta \kappa \lambda $$

with $\Delta \kappa = \Delta \kappa_2 = \Delta \kappa_3 \lambda = \lambda_2$.

The kinematic variable $X$ is chosen to be the $p_T$ of the $q\bar{q}$ system, which is highly sensitive to anomalous couplings, as demonstrated in Fig. 4. Depending on the number of reweighting coefficients, a system of the same number of equations allows us to calculate their values for each event. Applied on the SM distribution of $X$ for any combination of anomalous couplings, the distribution of $X$ weighted by $R$ corresponds to the kinematic distribution in the presence of the given non-SM TGC.

To calculate reweighting coefficients in the LEP parametrization scenario, we generate nine different functions, $F_i$ ($i = 1 - 9$), fitting the shape of the $p_T^q$ distributions in the presence of anomalous couplings. The values of anomalous TGCs are chosen to deviate $\pm 0.5$ relative to the SM as shown in Table II. We calculate nine weights $R_i$ normalizing the functions $F_i$ with the cross sections given by the HZW generator.

### TABLE II: The values of $\Delta \kappa_1$, $\lambda$, and $\Delta g_1^2$ used to calculate the reweighting coefficients $A(X) - I(X)$ in the LEP parametrization scenario.

| $F_3$ | $F_4$ | $F_5$ | $F_6$ | $F_7$ | $F_8$ | $F_9$ |
|--------|--------|--------|--------|--------|--------|--------|
| $\Delta \kappa_1$ | 0 | 0 | 0.5 | -0.5 | 0 | 0 | 0.5 | +0.5 | +0.5 | 0 |
| $\lambda$ | -0.5 | -0.5 | 0 | 0 | 0 | 0.5 | 0 | +0.5 | 0 |
| $\Delta g_1^2$ | 0 | 0 | 0 | 0 | +0.5 | -0.5 | 0 | 0.5 | +0.5 | 0 |

To verify the derived reweighting parameters, we calculated the weight $R$ for different $\Delta \kappa$, $\lambda$, and/or $\Delta g_1^2$ values, applied the reweighting coefficients and compared reweighted $p_T^q$ shapes to those predicted by the generator. Discrepancies in the $p_T^q$ shape of less than 5% and in normalization of less than 0.1% from those predicted by the generator represent reasonable agreement.

When measuring TGCs in the LEP parametrization, we vary two of the three couplings at a time, leaving the third coupling fixed to its SM value. This gives three two-parameter combinations ($\Delta \kappa$, $\lambda$, $\Delta g_1^2$), and ($\lambda$, $\Delta g_1^2$). For the equal couplings scenario there is only the ($\Delta \kappa$, $\lambda$) combination. In each case, the two couplings being evaluated are each varied between -1 and +1 in steps of 0.01. For a given pair of anomalous coupling values, each event in a reconstructed dijet $p_T$ is weighted by the appropriate weight $R$ and all the weights are summed in that bin. The observed limits are determined from a fit of background and reweighted signal MC distributions for different anomalous couplings contributions to the observed data using the dijet $p_T$ distribution of candidate events.

### VIII. SYSTEMATIC UNCERTAINTIES

We consider two general types of systematic uncertainties. Uncertainties of the first class (TYPE I) are related to the overall normalization and efficiencies of the various contributing physical processes. The largest contributing TYPE I uncertainties are those related to the accuracy of the theoretical cross section used to normalize the background processes. These uncertainties are considered to arise from Gaussian parent distributions.

The second class (TYPE II) consists of uncertainties that, when propagated through the analysis selection, impact the shape of the dijet $p_T$ distribution. The dependence of the dijet $p_T$ distribution on these uncertainties is determined by varying each parameter by its associated uncertainty ($\pm$1 s.d.) and reevaluating the shape of the dijet $p_T$ distribution. The resulting shape dependence is considered to arise from a Gaussian parent distribution.

Although TYPE II uncertainties may also impact efficiencies or normalization, any uncertainty shown to impact the shape of the dijet $p_T$ distribution is treated as TYPE II. Both types of systematic uncertainty are assumed to be 100% correlated amongst backgrounds and signals. All sources of systematic uncertainty are assumed to be mutually independent, and no intercorrelation is propagated. A list of the systematic uncertainties used in this analysis can be found in Table III.

### IX. ANOMALOUS COUPLING LIMITS

The fit utilizes the MINUIT [34] software package to minimize a Poisson $\chi^2$ with respect to variations to the systematic uncertainties [29]. The $\chi^2$ function used is

$$ \chi^2 = -2 \ln \left( \prod_{i=1}^{N_t} \frac{L^P(d_i;m_i(R))}{L^P(d_i)} \prod_{k=1}^{N_s} \frac{L^S(R_k;\sigma_k;0,\sigma_k)}{L^S(0;0,\sigma_k)} \right) $$
**TABLE III:** Systematic uncertainties in percent for Monte Carlo simulations and multijet estimates. Uncertainties are identical for both lepton channels except where otherwise indicated. The nature of the uncertainty, i.e., whether it refers to a normalization uncertainty (type I) or a shape dependence (type II), is also provided. The values for uncertainties with a shape dependence correspond to the maximum amplitude of shape fluctuations in the dijet $p_T$ distribution ($0 \text{ GeV} \leq p_T \leq 300 \text{ GeV}$) after ±1 s.d. parameter changes. However, the full shape dependence is included in the calculations.

| Source of systematic uncertainty | Diboson signal [%] | W+jets [%] | Z+jets [%] | Top [%] | Multijet [%] | Type |
|---------------------------------|-----------------|------------|------------|--------|-------------|------|
| Trigger efficiency, electron channel | $+2/-3$ | $+2/-3$ | $+2/-3$ | $+2/-3$ | I |
| Trigger efficiency, muon channel | $+0/-5$ | $+0/-5$ | $+0/-5$ | $+0/-5$ | II |
| Lepton identification | ±4 | ±4 | ±4 | ±4 | I |
| Jet identification | ±1 | ±1 | ±1 | <1 | II |
| Jet energy scale | ±4 | ±7 | ±5 | ±5 | II |
| Jet energy resolution | ±3 | ±4 | ±4 | ±4 | II |
| Luminosity | ±6.1 | ±6.1 | ±6.1 | ±6.1 | I |
| Cross section (including PDF uncertainties) | ±20 | ±6 | ±10 | I |

Lepton efficiencies depend on kinematics; however, their fractional uncertainties are much less kinematically dependent and have a negligible effect on the shape of the dijet $p_T$ distribution.

$$\chi^2 = 2 \sum_{i=1}^{N_b} m_i(\vec{R}) - d_i - d_i \ln \left( \frac{m_i(\vec{R})^2}{d_i} \right) + \sum_{k=1}^{N_s} R_k^2,$$

in which the indices $i$ and $k$ run over 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 $\alpha$ events with a mean of $\beta$ events; $\mathcal{L}^G(x; \mu, \sigma)$ is the Gaussian probability for $x$ events in a distribution with a mean value of $\mu$ and a variance $\sigma^2$. $R_k$ is a dimensionless parameter describing departures in nuisance parameters in units of the associated systematic uncertainty $\sigma_k$; $d_i$ is the number of data events in bin $i$; and $m_i(\vec{R})$ is the number of predicted events in bin $i$.[29]

Systematics are treated as Gaussian-distributed uncertainties on the expected numbers of signal and background events. The individual background contributions are fitted to the data by minimizing this $\chi^2$ function over the individual systematic uncertainties.[29] The fit computes the optimal central values for the systematic uncertainties, while accounting for departures from the nominal predictions by including a term in the $\chi^2$ function that sums the squared deviation of each systematic in units normalized by its ±1 s.d. uncertainties.

Figure[23] shows the dijet $p_T$ distributions in the combined electron and muon channels after the fit. The value of $\chi^2$ is measured between data and MC dijet $p_T$ distributions as the signal MC is varied in the presence of anomalous couplings. The $\Delta \chi^2$ values of 1 and 3.84 from the minimum $\chi^2$ in the parameter space, for which all other anomalous couplings are zero, represent the 68% confidence level (C.L.) and 95% C.L. limits, respectively. For the LEP parametrization, the most probable coupling values as measured in data with associated uncertainties at 68% C.L. are $\kappa = 1.07^{+0.26}_{-0.29}$, $\lambda = 0.00^{+0.06}_{-0.09}$, and $g_\gamma^Z = 1.04^{+0.09}_{-0.09}$. For the equal couplings scenario, the most probable coupling values as measured in data with associated uncertainties at 68% C.L. are $\kappa = 1.04^{+0.11}_{-0.10}$ and $\lambda = 0.00^{+0.06}_{-0.09}$. The observed 95% C.L. limits estimated from the single parameter fit are $-0.44 < \Delta \kappa < 0.55$, $-0.10 < \lambda < 0.11$, and $-0.12 < \Delta g_\gamma^Z < 0.20$ for the LEP parametrization or $-0.16 < \Delta \kappa < 0.23$ and $-0.11 < \lambda < 0.11$ for the equal couplings scenario (Table[14]).

The observed 68% C.L. and 95% C.L. limits in two-parameter space are shown in Figs[6] and [7] as a function of anomalous couplings along with the most probable values of $\Delta \kappa$, $\lambda$, and $\Delta g_\gamma^Z$. As shown in Table[15] the 95% C.L. limits on anomalous couplings $\Delta \kappa$, $\Delta \lambda$, and $\Delta g_\gamma^Z$ set using the dijet $p_T$ distribution of $WW/ZZ \to \ell\nu\ell\nu$ events are comparable with the 95% C.L. limits set by the D0 Collaboration from $WW$[3], $WZ$[4], and $W\gamma$[5] production in fully leptonic channels using $\approx 1 \text{ fb}^{-1}$ of data. The most recent 95% C.L. one-parameter limits from the CDF Collaboration under the equal couplings scenario at $\Lambda_{NP} = 1.5 \text{ TeV}$ are $-0.46 < \Delta \kappa < 0.39$ and $-0.18 < \lambda < 0.17$ using 350 pb$^{-1}$ of data, combining the $\ell\nu\ell\nu$ ($\ell = e, \mu$) final states[6]. These re-
γWW/ZWW boson pairs corresponding to 1.1 fb⁻¹ of pp collisions collected with the D0 detector at the Fermilab Tevatron Collider. The measurement is in agreement with the SM. On the other hand, this analysis yields the most stringent limits on γWW/ZWW anomalous couplings from the Tevatron to date, complementing similar measurements performed in fully leptonic decay modes from Wγ, WW, and WZ production.

![Image]

**TABLE IV:** The most probable values with total uncertainties (statistical and systematic) at 68% C.L. for κγ, λ, and g₁Z along with observed 95% C.L. one-parameter limits on Δκγ, λ, and Δg₁Z measured in 1.1 fb⁻¹ of WW/WZ → ℓνjj events with ΛNP = 2 TeV.

| 68% C.L.          | κγ | λ = λγ = λZ | g₁Z  |
|-------------------|----|-------------|------|
| LEP parametrization | κγ = 1.04⁺⁻0.26 | λ = 0.00⁺⁻0.06 | g₁Z = 1.04⁺⁻0.09 |
| Equal couplings   | κγ = κZ = 1.04⁺⁻0.11 | λ = 0.00⁺⁻0.06 | |

**TABLE V:** Comparison of 95% C.L. one-parameter TGC limits between the different channels studied at D0 with ≈ 1 fb⁻¹ of data: WW → ℓνℓν, Wγ → ℓνγ, WZ → ℓℓνγ and WW + WZ → ℓνjj (l = μ, e) at ΛNP = 2 TeV.

| LEP parametrization | Δκγ | λ = λγ = λZ | Δg₁Z  |
|---------------------|------|-------------|------|
| WW → ℓνℓν (1 fb⁻¹) | -    | -0.17 < λ < 0.21 | -0.14 < Δg₁Z < 0.34 |
| Wγ → ℓνγ (0.7 fb⁻¹) | -0.51 < Δκγ < 0.51 | -0.12 < λ < 0.13 |
| WW → ℓνℓν (1 fb⁻¹) | -0.54 < Δκγ < 0.83 | -0.14 < λ < 0.18 |
| WW + WZ → ℓνjj (1.1 fb⁻¹) | -0.44 < Δκγ < 0.55 | -0.10 < λ < 0.11 |

**equal couplings**

| Δκγ | λ = λγ = λZ | Δg₁Z  |
|------|-------------|------|
| WW → ℓνℓν (1 fb⁻¹) | -0.17 < λ < 0.21 |
| Wγ → ℓνγ (0.7 fb⁻¹) | -0.12 < λ < 0.13 |
| WW → ℓνℓν (1 fb⁻¹) | -0.12 < Δκγ < 0.35 |
| WW + WZ → ℓνjj (1.1 fb⁻¹) | -0.16 < Δκγ < 0.23 |

| 95% C.L.          | Δκγ | λ = λγ = λZ | Δg₁Z  |
|-------------------|------|-------------|------|
| LEP parametrization | -0.44 < Δκγ < 0.55 | -0.10 < λ < 0.11 | -0.12 < Δg₁Z < 0.20 |
| Equal couplings   | -0.16 < Δκγ < 0.23 | -0.11 < λ < 0.11 |

The measurement is in agreement with the SM. On the other hand, this analysis yields the most stringent limits on γWW/ZWW anomalous couplings from the Tevatron to date, complementing similar measurements performed in fully leptonic decay modes from Wγ, WW, and WZ production.
TABLE VI: Measured values of $\kappa_\gamma$, $\lambda$ and $g_1^Z$ couplings and their associated uncertainties at 68% C.L. obtained from the one-parameter fits combining data from different topologies and energies at LEP2 experiments. The last column shows the D0 result obtained from the $\ell v jj$ final states only selected from 1 fb$^{-1}$ of data. The uncertainties include both statistical and systematic sources.

| 68% C.L. | ALEPH          | OPAL           | L3             | D0 ($\ell v jj$) |
|----------|----------------|----------------|----------------|-----------------|
| $\kappa_\gamma$ | 0.971±0.063 | 0.88±0.09 | 1.013±0.071 | 1.07±0.26 |
| $\lambda$     | -0.012±0.029 | -0.060±0.034 | -0.021±0.039 | 0.00±0.06 |
| $g_1^Z$        | 1.001±0.030 | 0.987±0.033 | 0.966±0.036 | 1.04±0.09 |

FIG. 3: Semileptonic production cross sections for (a) $WW$ and (b) $WZ$ normalized to the SM prediction as a function of anomalous coupling $\Delta \kappa (\lambda = \Delta g_1^Z = 0)$ in the LEP parametrization scenario. The new physics scale $\Lambda_{NP}$ is set to 2 TeV.

FIG. 4: Normalized distributions of the hadronic W boson (a) $p_T$ and (b) rapidity at the parton level in $WW$ production including anomalous couplings under the LEP parametrization scenario: $\Delta \kappa_\gamma = +0.5$ ($\lambda = \Delta g_1^Z = 0, \Delta \kappa_Z = -0.15$), $\lambda = +0.5$ ($\Delta \kappa_\gamma = \Delta \kappa_Z = \Delta g_1^Z = 0$), and $\Delta g_1^Z = +0.5$ ($\Delta \kappa_\gamma = \lambda = 0, \Delta \kappa_Z = 1.5$) compared to the SM distribution for $WW$ production with unity normalization. The new physics scale $\Lambda_{NP}$ is set to 2 TeV.
FIG. 5: (a) The dijet $p_T$ distribution of combined (electron+muon) channels for data and SM predictions following the fit of MC to data. (b) The difference between data and simulation divided by the uncertainty (statistical and systematic) for the dijet $p_T$ distribution. Also shown are the MC signals for anomalous couplings corresponding to the 95% C.L. limits for $\Delta \kappa$ and $\lambda$ in the LEP parametrization scenario. The full error bars on the data points reflect the total (statistical and systematic) uncertainty, with the ticks indicating the contribution due only to the statistical uncertainty.

FIG. 6: The 68% C.L. and 95% C.L. two-parameter limits on the $\gamma_{WW/ZW}$ coupling parameters $\Delta \kappa_Y$, $\lambda$, and $\Delta g^Z_1$, in the LEP parametrization scenario and $\Lambda_{NP} = 2$ TeV. The dots indicate the most probable values of anomalous couplings from the two-parameter combined (electron+muon) fit and the star markers denote the SM prediction.
FIG. 7: The 68% C.L. and 95% C.L. two-parameter limits on the $\gamma W W/Z W W$ coupling parameters $\Delta \kappa$ and $\lambda$, in the equal couplings scenario and $\Lambda_{NP} = 2$ TeV. The dot indicates the most probable values of anomalous couplings from the two-parameter combined (electron+muon) fit and the star marker denotes the SM prediction.
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