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Limits on anomalous $WW\gamma$ and WWZ couplings

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Limits on the anomalous $WW\gamma$ and WWZ couplings are presented from a simultaneous fit to the data samples of three gauge boson pair final states in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV: $W\gamma$ production with the W boson decaying to $e\nu$ or $\mu\nu$, W boson pair production with both of the W bosons decaying to $e\nu$ or $\mu\nu$, and WW or WZ production with one W boson decaying to $e\nu$ and the other W boson or the Z boson decaying to two jets. Assuming identical $WW\gamma$ and WWZ couplings, 95% C.L. limits on the anomalous couplings of $-0.30<\Delta\kappa<0.43$ $(\lambda=0)$ and $-0.20<\lambda<0.20$ $(\Delta\kappa=0)$ are obtained using a form factor scale $\Lambda=2.0$ TeV. Limits found under other assumptions on the relationship between the $WW\gamma$ and WWZ couplings are also presented. [S0556-2821(98)50615-7]

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Gauge boson self-interactions are a direct consequence of the non-Abelian $SU(2)\times U(1)$ gauge symmetry of the standard model (SM) and are a necessary element to construct unitary and renormalizable theories involving massive gauge bosons [1]. The values of trilinear gauge boson couplings are fully determined in the SM by the gauge structure. The precise determination of the couplings constitutes one of few remaining tests of the SM; any deviation from the SM values would indicate the presence of new physics. Phenomenological bounds on the trilinear gauge boson couplings have been obtained from the precisely measured quantities, such as $(g-2)_\mu$, the $b\to s\gamma$ decay rate, the $Z\to b\bar{b}$ rate and oblique corrections [2]. These bounds are obtained with many assumptions imposed on the couplings. The trilinear gauge boson couplings can be measured directly with fewer assump-

tions by studying gauge boson pair production processes. Direct measurements of the couplings have been reported by the UA2 [3], Collider Detector at Fermilab (CDF) [4,6,9], D0 [5,7,8,10], and CERN e^+e^- collider LEP [11] Collaborations. Hadron collider experiments have established the electromagnetic coupling of the W boson to the photon [3–5] and the existence of the coupling between the W boson and the Z boson [6–10] by placing constraints on anomalous $WW\gamma$ and WWZ couplings.

The $WW\gamma$ and WWZ vertices are described by a general effective Lagrangian with two overall coupling constants, $g_{WW\gamma}=-e$ and $g_{WWZ}=-e\cdot\cot\theta_W$ (where e is the W^+ charge and θ_W is the weak mixing angle), and six dimensionless coupling parameters, g_1^V, κ_V, and λ_V ($V=\gamma$ or Z), after imposing C, P, and CP invariance [12]. Electromagnetic gauge invariance requires that $g_1^\gamma=1$, which we assume throughout this paper. The effective Lagrangian becomes that of the SM when $g_1^\gamma=g_1^Z=1$ ($\Delta g_1^V\equiv g_1^V-1=0$), $\kappa_V=1$ ($\Delta\kappa_V\equiv\kappa_V-1=0$), and $\lambda_V=0$. Limits on these couplings are usually obtained under the assumption that the $WW\gamma$ and WWZ couplings are equal ($g_1^\gamma=g_1^Z=1$, $\Delta\kappa_\gamma=\Delta\kappa_Z$, and $\lambda_\gamma=\lambda_Z$).

A different set of parameters, motivated by $SU(2)\times U(1)$ gauge invariance, has been used by the LEP collaborations [13]. This set consists of three independent couplings $\alpha_{B\phi}$, $\alpha_{W\phi}$ and α_W: $\alpha_{B\phi}\equiv\Delta\kappa_\gamma-\Delta g_1^Z\cos^2\theta_W$, $\alpha_{W\phi}\equiv\Delta g_1^Z\cos^2\theta_W$ and $\alpha_W\equiv\lambda_\gamma$. The remaining WWZ coupling parameters λ_Z and $\Delta\kappa_Z$ are determined by the relations $\lambda_Z=\lambda_\gamma$ and $\Delta\kappa_Z=-\Delta\kappa_\gamma\tan^2\theta_W+\Delta g_1^Z$. The Hagiwara-Ishihara-Szalapski-Zeppenfeld (HISZ) relations [14] which have been used by the D0 and CDF collaborations are also based on this set with the additional constraint $\alpha_{B\phi}=\alpha_{W\phi}$.

Non-SM couplings give rise to a large increase in the cross section of gauge boson pair production processes at high energies. To avoid violation of unitarity, the anomalous couplings are modified by form factors with a scale Λ [e.g., $\lambda_V(\hat{s})=\lambda_V/(1+\hat{s}/\Lambda^2)^2$], which is related to the scale of new physics.

The D0 collaboration has previously reported limits on anomalous $WW\gamma$ and WWZ couplings from the data samples of three gauge boson pair final states: $W\gamma$ production with the W boson decaying to $e\nu$ or $\mu\nu$ [5], W boson pair production with both of the W bosons decaying to $e\nu$ or $\mu\nu$ [7], and WW or WZ production with one W boson decaying to $e\nu$ and the other W boson or the Z boson decaying to two jets [8]. The data samples correspond to an integrated luminosity of approximately 100 pb^{-1} collected with the D0 detector during the 1992–93 and 1993–1995 Tevatron collider runs at Fermilab. This report is a culmination of these studies and presents the most stringent limits available on anomalous $WW\gamma$ and WWZ couplings by performing a simultaneous fit to the data samples of the above three final states. Limits are also set on the α parameters, enabling a direct comparison of our results with those of LEP experiments.

The D0 detector and data collection system are described elsewhere [15]. Limits on the anomalous couplings are obtained by a maximum likelihood fit to the transverse energy (E_T) spectrum of a final state gauge boson or to the E_T spectra of the decay leptons from the gauge boson pair. Since the predicted relative increase in the gauge boson pair production cross section with anomalous couplings is greater at higher gauge boson E_T, fits to the E_T spectra provide significantly tighter constraints on anomalous couplings than those from the measurement of the cross section alone. The individual analyses have been described in detail previously [10]. This paper reports only on the simultaneous fit to the three data sets.

TABLE I. Limits at 95% C.L. from the $W\gamma$ analysis.

	$\Lambda=1.5$ TeV
λ_γ ($\Delta\kappa_\gamma=0$)	−0.31, 0.29
$\Delta\kappa_\gamma$ ($\lambda_\gamma=0$)	−0.93, 0.94

In this analysis, as in the previous reports, a binned maximum likelihood fit is performed to the candidate events. The probability P_i for observing N_i events in a given bin of a kinematical variable is $P_i=e^{-(b_i+n_i)}(b_i+n_i)^{N_i}/N_i!$, where b_i is the estimated background, $n_i(=\mathcal{L}\epsilon\sigma_i(\lambda,\Delta\kappa))$ is the expected signal, $\mathcal{L}$ is the integrated luminosity, ϵ is the detection efficiency, and σ_i is the theoretical cross section which is a function of anomalous couplings, λ and $\Delta\kappa$. The joint probability P for all the kinematical bins that are fitted is $P=\Pi_{i=1}^{N_{bin}}P_i$. Since the variables b_i, $\mathcal{L}$, ϵ and the normalization of the predicted theoretical cross section are estimated quantities with some uncertainty and do not depend on λ and $\Delta\kappa$, we assign Gaussian prior distributions and integrate over the possible ranges; $P'\propto\int\mathcal{G}_{f_n}df_n\int\mathcal{G}_{f_b}df_b\ \ \Pi_{i=1}^{N_{bin}}e^{-(f_nn_i+f_bb_i)}(f_nn_i+f_bb_i)^{N_i}/N_i!$, where $\mathcal{G}_{f_b}$ and $\mathcal{G}_{f_n}$ are Gaussian functions with standard deviation σ_b and σ_n for the background and the signal, respectively. For convenience, the log-likelihood, $L=-\log P'$, is used. When the simultaneous fit is performed on the three data sets, correlations between σ_b and σ_n for different final states are carefully taken into account.

In Table I, the 95% C.L. limits on anomalous $WW\gamma$ couplings from the $W\gamma$ analysis are listed. The $W\gamma$ candidate events are selected by requiring an isolated high E_T electron or muon, large missing transverse energy ($\not{E}_T$) and an isolated high E_T photon. The limits are obtained from a binned maximum likelihood fit to the E_T spectrum of the photons. In this process, only λ_γ and $\Delta\kappa_\gamma$ couplings are involved.

In Table II, the 95% C.L. limits from the $WW\rightarrow$dilepton analysis are listed. The $WW\rightarrow$dilepton candidate

TABLE II. Limits at 95% C.L. from the $WW\rightarrow$dilepton analysis.

	$\Lambda=1.5$ TeV
$\lambda_\gamma=\lambda_Z$ ($\Delta\kappa_\gamma=\Delta\kappa_Z=0$)	−0.53, 0.56
$\Delta\kappa_\gamma=\Delta\kappa_Z$ ($\lambda_\gamma=\lambda_Z=0$)	−0.62, 0.77
λ_γ(HISZ) ($\Delta\kappa_\gamma=0$)	−0.53, 0.56
$\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma=0$)	−0.92, 1.20

TABLE III. Limits at 95% C.L. from the $WW/WZ \to e\nu jj$ analysis.

Λ	1.5 TeV	2.0 TeV
$\lambda_\gamma = \lambda_Z$ ($\Delta\kappa_\gamma = \Delta\kappa_Z = 0$)	−0.36, 0.39	−0.34, 0.36
$\Delta\kappa_\gamma = \Delta\kappa_Z$ ($\lambda_\gamma = \lambda_Z = 0$)	−0.47, 0.63	−0.43, 0.59
λ_γ(HISZ) ($\Delta\kappa_\gamma = 0$)	−0.36, 0.39	−0.34, 0.36
$\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma = 0$)	−0.56, 0.85	−0.53, 0.78
λ_Z(SM $WW\gamma$) ($\Delta\kappa_Z = \Delta g_1^Z = 0$)	−0.40, 0.43	−0.37, 0.40
$\Delta\kappa_Z$(SM $WW\gamma$) ($\lambda_Z = \Delta g_1^Z = 0$)	−0.60, 0.79	−0.54, 0.72
Δg_1^Z(SM $WW\gamma$) ($\lambda_Z = \Delta\kappa_Z = 0$)	−0.64, 0.89	−0.60, 0.81
λ_γ(SM WWZ) ($\Delta\kappa_\gamma = 0$)	−1.21, 1.25	–
$\Delta\kappa_\gamma$(SM WWZ) ($\lambda_\gamma = 0$)	−1.38, 1.70	–

events are selected by requiring two high E_T leptons (ee, $e\mu$, or $\mu\mu$) and large $\not{E}_T$. The limits are obtained from a maximum likelihood fit to the number of observed candidate events in two-dimensional E_T bins of the decay leptons from the W boson pair.

In Table III, the 95% C.L. limits from the $WW/WZ \to e\nu jj$ analysis are listed. The $WW/WZ \to e\nu jj$ candidate events are selected by requiring an isolated high E_T electron, large $\not{E}_T$, and two high E_T jets. The invariant mass of the two jet system must be consistent with that of the W or Z boson. Limits are obtained from a binned maximum likelihood fit to the E_T spectrum of the W boson calculated from the electron E_T and $\not{E}_T$, using four sets of relationships between the $WW\gamma$ and WWZ couplings: (i) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$, (ii) HISZ relations, (iii) varying the WWZ couplings, while the $WW\gamma$ couplings are fixed to the SM values, and (iv) varying the $WW\gamma$ couplings, while the WWZ couplings are fixed to the SM values. Two values of Λ, 1.5 and 2.0 TeV, are used.

Tables I–III are reproduced from the previous reports. Figure 1 contains the 95% C.L. two-degree of freedom exclusion contours [16] from the $W\gamma$, $WW \to$dilepton, and $WW/WZ \to e\nu jj$ analyses. The contours that represent the unitarity constraint [17] for individual processes are omitted in Fig. 1.

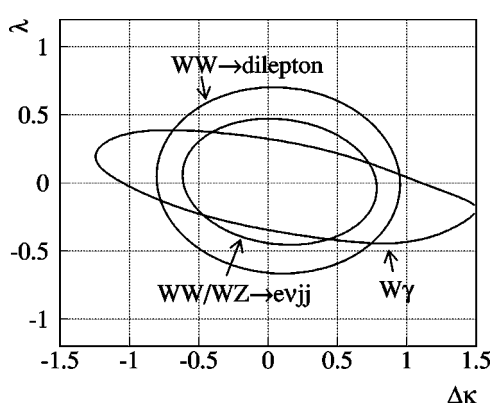

FIG. 1. Contour limits on anomalous couplings for $\Lambda = 1.5$ TeV. For the $WW \to$dilepton and $WW/WZ \to e\nu jj$ contour limits, the $WW\gamma$ and WWZ couplings are assumed to be equal. The contours plotted in Figs. 1–3 are accurate to ± 0.02 due to MC statistics.

TABLE IV. Limits at 95% C.L. from a simultaneous fit to the $W\gamma$, $WW \to$dilepton and $WW/WZ \to e\nu jj$ data samples. The four sets of limits apply the same assumptions as the four components (a), (b), (c) and (d), respectively, of Fig. 2.

Λ	1.5 TeV	2.0 TeV
$\lambda_\gamma = \lambda_Z$ ($\Delta\kappa_\gamma = \Delta\kappa_Z = 0$)	−0.21, 0.21	−0.20, 0.20
$\Delta\kappa_\gamma = \Delta\kappa_Z$ ($\lambda_\gamma = \lambda_Z = 0$)	−0.33, 0.46	−0.30, 0.43
λ_γ(HISZ) ($\Delta\kappa_\gamma = 0$)	−0.21, 0.21	−0.20, 0.20
$\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma = 0$)	−0.39, 0.61	−0.37, 0.56
λ_Z(SM $WW\gamma$) ($\Delta\kappa_Z = \Delta g_1^Z = 0$)	−0.33, 0.37	−0.31, 0.34
$\Delta\kappa_Z$(SM $WW\gamma$) ($\lambda_Z = \Delta g_1^Z = 0$)	−0.46, 0.64	−0.42, 0.59
Δg_1^Z(SM $WW\gamma$) ($\lambda_Z = \Delta\kappa_Z = 0$)	−0.56, 0.86	−0.52, 0.78
λ_γ(SM WWZ) ($\Delta\kappa_\gamma = 0$)	−0.27, 0.25	−0.26, 0.24
$\Delta\kappa_\gamma$(SM WWZ) ($\lambda_\gamma = 0$)	−0.63, 0.75	−0.59, 0.72

In Table IV, the 95% C.L. limits from a simultaneous fit to the three data sets are presented. The common uncertainties, those on the integrated luminosity (5.3%) and the theoretical cross section of the gauge boson pair production (7%), are factored out and included only once in the integration. Correlations in the uncertainties on the electron and muon selection efficiencies between the data sets of the 1992–1993 and 1993–1995 runs are properly taken into account for individual final states. Correlations in the uncer-

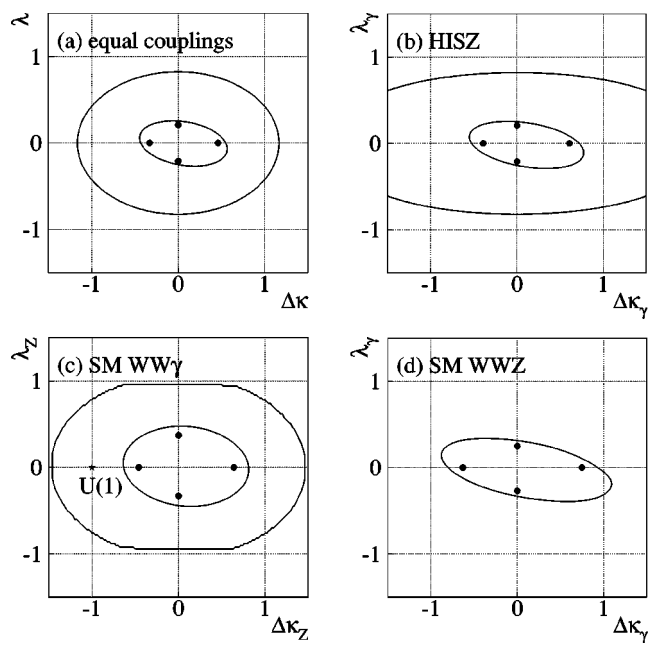

FIG. 2. Contour limits on anomalous couplings from a simultaneous fit to the data sets of $W\gamma$, $WW \to$dilepton, and $WW/WZ \to e\nu jj$ final states for $\Lambda = 1.5$ TeV: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) SM $WW\gamma$ couplings; and (d) SM WWZ couplings. (a), (c), and (d) assume that $\Delta g_1^Z = 0$. The solid circles correspond to 95% C.L. one-degree of freedom exclusion limits. The inner and outer curves are 95% C.L. two-degree of freedom exclusion contour and the constraint from the unitarity condition, respectively. In (d), the unitarity contour is located outside of the boundary of the plot.

TABLE V. Limits at 95% C.L. on α parameters from a simultaneous fit to the $W\gamma$, $WW\rightarrow$dilepton and $WW/WZ\rightarrow e\nu jj$ data samples. Limits from the OPAL collaboration based on data taken at $\sqrt{s}=172$ GeV are also listed for comparison.

Λ	1.5 TeV	2.0 TeV	OPAL
$\alpha_{B\phi}$ ($\alpha_{W\phi}=\alpha_W=0$)	$-0.81,\ 0.61$	$-0.77,\ 0.58$	$-1.6,\ 2.7$
$\alpha_{W\phi}$ ($\alpha_{B\phi}=\alpha_W=0$)	$-0.24,\ 0.46$	$-0.22,\ 0.44$	$-0.55,\ 0.64$
α_W ($\alpha_{B\phi}=\alpha_{W\phi}=0$)	$-0.21,\ 0.21$	$-0.20,\ 0.20$	$-0.78,\ 1.19$
Δg_1^Z ($\alpha_{B\phi}=\alpha_W=0$)	$-0.31,\ 0.60$	$-0.29,\ 0.57$	$-0.75,\ 0.77$

tainties on the electron and muon selection efficiencies between different final states are ignored, since the uncertainties themselves are small and have practically no effect on the limits. Correlations in the uncertainties on the background estimates between the data sets of the 1992–1993 and 1993–1995 runs are properly taken into account for individual final states. The uncertainties on the background estimates between different final states are assumed to be uncorrelated, since the dominant sources of uncertainties are different for the three final states. Figure 2(a) shows the contour limits when the $WW\gamma$ and WWZ couplings are assumed to be equal. Figure 2(b) shows the contour limits assuming HISZ relations. In Fig. 2(c), the contour limits on anomalous WWZ couplings are shown assuming the SM $WW\gamma$ couplings. The $U(1)$ point ($\kappa_Z=0$, $\lambda_Z=0$ and $g_1^Z=0$) indicated in the figure, which implies that there is no coupling between the W boson and the Z boson, is excluded at the 99.99% C.L. In Fig. 2(d), the contour limits on anomalous $WW\gamma$ couplings are shown assuming the SM WWZ couplings. The solid circles correspond to 95% C.L. one-degree of freedom exclusion limits. The inner and outer curves are 95% C.L. two-degree of freedom exclusion contour [16] and the constraint from the unitarity condition with $\Lambda=1.5$ TeV, respectively.

In Table V, the 95% C.L. limits on the α parameters from a simultaneous fit to the three data sets are presented. Limits on Δg_1^Z are obtained, from the limits on $\alpha_{W\phi}$ for $\alpha_{B\phi}=\alpha_W=0$. For comparison, limits from the OPAL collaboration based on data taken at $\sqrt{s}=172$ GeV [11] are also listed in Table V. Limits from other LEP collaborations are similar to those from OPAL. Figure 3(a) shows the contour limits in the α_W-$\alpha_{B\phi}$ plane, when $\alpha_{W\phi}=0$. Figure 3(b) shows the contour limits in the α_W-$\alpha_{W\phi}$ plane, when $\alpha_{B\phi}=0$.

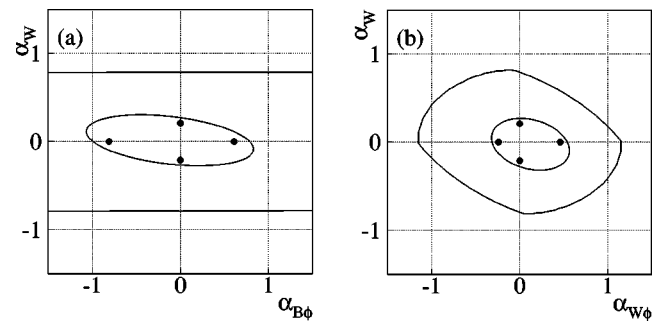

FIG. 3. Contour limits on anomalous couplings from a simultaneous fit to the data sets of the $W\gamma$, $WW\rightarrow$dilepton, and $WW/WZ\rightarrow e\nu jj$ final states for $\Lambda=1.5$ TeV: (a) α_W vs $\alpha_{B\phi}$ when $\alpha_{W\phi}=0$; and (b) α_W vs $\alpha_{W\phi}$ when $\alpha_{B\phi}=0$. The solid circles correspond to 95% C.L. one-degree of freedom exclusion limits. The inner and outer curves are 95% C.L. two-degree of freedom exclusion contour and the constraint from the unitarity condition, respectively.

In summary, limits on the anomalous $WW\gamma$ and WWZ couplings are obtained from a simultaneous fit to the data samples of three gauge boson pair final states. These limits are the tightest limits available on the anomalous $WW\gamma$ and WWZ couplings.

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