Search for Anomalous WW and WZ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present results from a search for anomalous WW and WZ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We used $p\bar{p} \rightarrow e\nu jjX$ events observed during the 1992–1993 run of the Fermilab Tevatron collider, corresponding to an integrated luminosity of $13.7 \pm 0.7\,\mathrm{pb}^{-1}$. A fit to the transverse momentum spectrum of the W boson yields direct limits on the CP-conserving anomalous $WW\gamma$ and WWZ coupling parameters of $-0.9 < \Delta\kappa < 1.1$ (with $\lambda = 0$) and $-0.6 < \lambda < 0.7$ (with $\Delta\kappa = 0$) at the 95% confidence level, for a form factor scale $\Lambda = 1.5$ TeV, assuming that the $WW\gamma$ and WWZ coupling parameters are equal.

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Self-interactions of the electroweak gauge bosons such as $WW\gamma$ and WWZ are a direct consequence of the non-Abelian gauge symmetry of the Standard Model (SM). The strength of these interactions can be directly measured by studying gauge boson pair production in $p\bar{p}$ collisions [1]. For example, WW production is sensitive to the $WW\gamma$ and WWZ couplings, and WZ production is sensitive to the WWZ coupling. Any deviation of these couplings from their SM values indicates physics beyond the SM.

The $WW\gamma$ and WWZ interactions are generally described by a Lagrangian with fourteen independent coupling parameters [2], of which κ_γ and λ_γ for the $WW\gamma$ vertex and κ_Z and λ_Z for the WWZ vertex are usually studied. These are CP-conserving coupling parameters. In the SM, $\Delta\kappa_\gamma(\equiv \kappa_\gamma - 1) = \lambda_\gamma = \Delta\kappa_Z(\equiv \kappa_Z - 1) = \lambda_Z = 0$, and the production cross section for $p\bar{p} \to W^+W^-X$ ($W^\pm ZX$) at $\sqrt{s} = 1.8$ TeV is 9.5 (2.5) pb [1].

Non-SM (i.e., anomalous) couplings dramatically increase the production cross section, and enhance the transverse momentum spectrum of the W boson (p_T^W) for large values of p_T^W. Therefore, a study of the p_T^W spectrum of $WW(WZ)$ production leads to a sensitive test of the size of the $WW\gamma$ and WWZ couplings. With anomalous couplings, some helicity amplitudes of the $p\bar{p} \to WW(WZ)$ processes grow with $\hat{s}$, the square of the invariant mass of the $WW(WZ)$ system, and cause the cross section eventually to violate tree level S–matrix unitarity. To avoid this, the anomalous couplings are commonly parametrized as dipole form factors with a cut-off scale Λ: $\Delta\kappa(\hat{s}) = \Delta\kappa/(1+\hat{s}/\Lambda^2)^2$, $\lambda(\hat{s}) = \lambda/(1+\hat{s}/\Lambda^2)^2$. Consequently, limits on the couplings $\Delta\kappa$ and λ are dependent on the choice of Λ.

The DØ collaboration has reported limits on $WW\gamma$ and WWZ anomalous couplings from two processes using data from the 1992–1993 Fermilab Tevatron collider run with $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV: on the $WW\gamma$ coupling from a measurement of $W\gamma$ production [3] and on the $WW\gamma$ and WWZ couplings from a search for W boson pair production in the dilepton decay modes [4]. In this letter we present a new, independent, determination of limits on the $WW\gamma$ and WWZ anomalous couplings obtained from a search for $p\bar{p} \to WWX$ followed by $W \to e\nu$ and $W \to jj$, and $p\bar{p} \to WZX$ followed by $W \to e\nu$ and $Z \to jj$, where j represents a jet. Owing to the limited jet energy resolution, we cannot distinguish WZ events from WW events. This analysis uses the same data set as in the papers cited above, corresponding to an integrated luminosity of 13.7 ± 0.7 pb^{-1}. The CDF collaboration has reported a similar measurement [5].

The DØ detector and data collection systems are described in Ref. [6]. The basic elements of the trigger and reconstruction algorithms for jets, electrons and neutrinos are given in Ref. [7].

The $WW, WZ \to e\nu jj$ candidates were selected by searching for events containing a $W \to e\nu$ decay and at least two jets consistent with $W \to jj$ or $Z \to jj$. The data sample was obtained with a trigger which required an isolated electromagnetic (EM) calorimeter cluster with transverse energy $E_T > 20$ GeV. In offline event selection, this EM cluster was required to be within $|\eta| \le 1.1$ in the central calorimeter, or $1.5 \le |\eta| \le 2.5$ in the end calorimeters, where η is the pseudorapidity, defined as $\eta = -\ln[\tan\theta/2]$ and θ is the polar angle with respect to the proton beam direction. Such an EM cluster was identified as an electron if (i) the ratio of EM energy to the total shower energy was greater than 0.9; (ii) the lateral and longitudinal shower shapes were consistent with those of an electron; (iii) the isolation variable of the cluster was less than 0.1, where isolation is defined as $I = (E_{\rm tot}(0.4) - E_{\rm EM}(0.2))/E_{\rm EM}(0.2)$, and $E_{\rm tot}(0.4)$ is the total calorimeter energy inside a cone of radius $\mathcal{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, where ϕ is the azimuthal angle around the beam axis and $E_{\rm EM}(0.2)$ is the EM energy inside a cone of radius 0.2; and (iv) a matching track was found in the drift chambers. The $W \to e\nu$ decay was identified by an electron with $E_T^e > 25$ GeV and missing transverse energy $\not{E}_T > 25$ GeV forming a transverse mass $M_T^{e\nu} = [2E_T^e \not{E}_T(1-\cos\phi^{e\nu})/c^4]^{1/2} > 40$ GeV$/c^2$, where $\phi^{e\nu}$ is the angle between the $\vec{E}_T^e$ and $\vec{\not{E}}_T$ vectors.

Jets were reconstructed using a cone algorithm with radius $\mathcal{R} = 0.3$, and were required to be within $|\eta| < 2.5$. The jet energies were corrected for detector effects: jet energy scale calibration and out-of-cone showering; for energy from the underlying event; and for energy loss due to out-of-cone gluon radiation [7]. We required that a candidate event contain at least two jets with $E_T^j > 20$ GeV and that the dijet invariant mass (the largest invariant mass if there were more than two jets with $E_T^j > 20$ GeV in the event) satisfy 50 GeV$/c^2 < m_{jj} <$ 110 GeV$/c^2$, consistent with W and Z boson masses. Monte Carlo studies showed that the standard deviation of the dijet invariant mass distribution of the signal events is 15 GeV$/c^2$. The above selection criteria yielded 84 candidate events.

The trigger and electron selection efficiencies were measured [8] using $Z \to ee$ events. The product of these efficiencies was found to be 0.78 ± 0.02 in the central calorimeter and 0.62 ± 0.01 in the end calorimeters. The $W \to jj$ selection efficiency was parametrized as a function of p_T^W, as shown in Fig. 1. This was estimated using events generated with the ISAJET [9] and PYTHIA [10] programs, followed by a detailed simulation of the DØ detector based on the GEANT package [11] and application of our event selection criteria. The roll-off of efficiency in the p_T^W region beyond ~ 350 GeV$/c$ is due to merging of the two jets from the W or Z boson. The use of a cone size as narrow as $\mathcal{R} = 0.3$ for jet reconstruction ensures that the loss of efficiency occurs only for W and Z bosons with transverse momenta greater than expected from the coupling parameter values studied. The $Z \to jj$ efficiency was obtained in a similar manner. In estimating the detection efficiencies of the $WW(WZ)$ process, we used the $W(Z) \to jj$ efficiency obtained from ISAJET, which is smaller than that from PYTHIA and therefore gives more conservative limits on the coupling parameters.

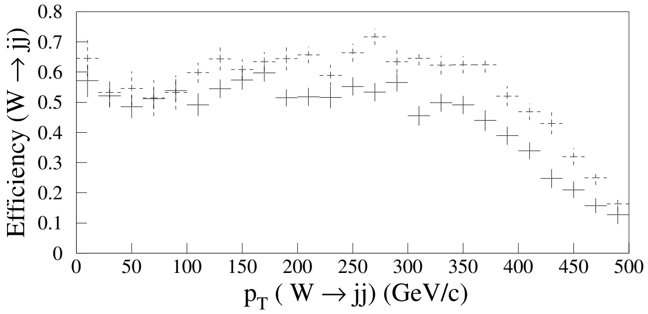

FIG. 1. Total efficiency for $W \to jj$ selection as a function of p_T^W, estimated using the ISAJET (solid) and PYTHIA (dashed) generators followed by a full detector simulation.

We calculated the overall event selection efficiency as a function of the coupling parameters using a fast detector simulation program which incorporates the efficiencies described above and the detector resolutions [7]. The $WW(WZ)$ events were generated with the Monte Carlo program of Zeppenfeld [1,12], in which the processes were generated to leading order, and higher order QCD effects on the cross section were approximated by a factor $K = 1 + \frac{8}{9}\pi\alpha_s = 1.34$. We included the p_T distribution of the ISAJET WW events in the simulation of the $WW(WZ)$ production. We calculated the total efficiency for SM couplings to be 0.15 ± 0.02 for WW and 0.16 ± 0.02 for WZ. The error is 13%, which is the addition in quadrature of the uncertainties on the electron trigger and selection efficiencies (2%), on the $W(Z) \to jj$ efficiency due to the difference between the ISAJET and PYTHIA programs (9%), the statistics of the Monte Carlo samples (4%), $\not{E}_T$ smearing (6%) and jet energy scale (6%). Therefore, 3.2 ± 0.6 WW and WZ events are expected based on the SM (2.8 ± 0.6 WW events plus 0.4 ± 0.1 WZ events). The error here is the sum in quadrature of the uncertainty in the efficiency above and that of the higher order QCD corrections to the signal prediction (14%) [5].

TABLE I. Summary of $e\nu jj$ data and backgrounds.

Background source	$e\nu jj$ events
multijets	12.2 ± 2.6
$W+ \geq 2j$	62.2 ± 13.0
$t\bar{t}(m_t = 180$ GeV/$c^2)$	0.87 ± 0.12
$WW, WZ \to \tau\nu jj$	0.22 ± 0.02
$ZX \to eeX$	$0.00^{+0.34}_{-0.00}$
Total Background	75.5 ± 13.3
Data	84
SM $WW + WZ$ prediction	3.2 ± 0.6

The background estimate, summarized in Table I, includes contributions from: multijet events, where a jet was misidentified as an electron and there was significant (mismeasured) missing transverse energy; $W+ \geq 2j$ events with $W \to e\nu$; $t\bar{t} \to W^+W^-b\bar{b} \to e\nu jjX$; $WW(WZ)$ with $W \to \tau\nu$ followed by $\tau \to e\nu\bar{\nu}$; and $ZX \to eeX$ where one electron was not identified.

The multijet background was estimated from the data by measuring the $\not{E}_T$ distribution of a background-dominated sample, which was obtained by selecting events containing an EM cluster that failed at least one of the electron identification requirements (ii) to (iv) described previously (shower shape, isolation or track-match). The $\not{E}_T$ distribution of this sample was scaled to match the candidate sample in the region 0 GeV $< \not{E}_T <$ 15 GeV (before the $\not{E}_T$ requirement was applied), where the contribution of signal events is negligible; then the portion of this distribution passing the $\not{E}_T$ requirement ($\not{E}_T >$ 25 GeV) was taken as our estimate of the multijet background, giving $12.2 \pm 2.3(\text{stat.}) \pm 1.1(\text{syst.})$ events. The $W+ \geq 2j$ background was estimated using the VECBOS Monte Carlo program [13], with $Q^2 = m_W^2$, followed by parton fragmentation using the ISAJET program and a detailed detector simulation. We normalized the number of VECBOS $W+ \geq 2j$ events to the number of observed $W+ \geq 2j$ events (after multijet events were subtracted) outside of the dijet mass signal region. This yielded $62.2 \pm 8.2(\text{stat.}) \pm 10.1(\text{syst.})$ $W+ \geq 2j$ background events inside the m_{jj} signal region, where the statistical uncertainty is due to the size of the VECBOS $W+ \geq 2j$ event sample and of all samples used to calculate the normalization factor (13%), and the systematic error is due to the normalization and to the jet energy scale correction (16%). The $W+ \geq 2j$ cross section obtained with this normalization procedure was consistent with the VECBOS prediction. The backgrounds due to $t\bar{t} \to W^+W^-b\bar{b}$ [14], $WW(WZ) \to \tau\nu jj$ [1] and $ZX \to eeX$ were estimated using the ISAJET program followed by the GEANT detector simulation and found to be small. The total background from all sources was estimated to be 75.5 ± 13.3 events. Therefore, we observed no statistically significant signal above the background. Figure 2 shows the p_T distribution of the $e\nu$ system of the data events, background estimates, and Monte Carlo predictions of WW and WZ production for SM couplings and for one example with anomalous couplings.

Using the efficiencies for SM WW and WZ production, the background-subtracted signal, the branching fractions $B(W \to e\nu)$, $B(W \to$ hadrons) and $B(Z \to$ hadrons) from Ref. [15], and assuming the SM ratio of the cross sections of $p\bar{p} \to W^+W^-X$ and $p\bar{p} \to W^\pm ZX$, we set an upper limit at the 95% confidence level (CL) on the cross section $\sigma(p\bar{p} \to W^+W^-X)$ of 183 pb.

The absence of an excess of events with high p_T^W excludes large deviations from the SM couplings. To set limits on the anomalous coupling parameters, we performed a binned likelihood fit on the entire p_T^W spectrum. For each p_T^W bin in the likelihood fit, and for a given set of anomalous coupling parameter values, we calculated the probability for the sum of the background and the predicted signal to fluctuate to the observed number of events. The uncertainties in the efficiency, background estimates, integrated luminosity and higher order QCD corrections to the signal prediction were convoluted in the likelihood function with Gaussian distributions. Our analysis is sensitive to anomalous couplings at both large and small $\hat{s}$, since we do not require high p_T^W, and therefore we retain events with small $\hat{s}$ [16].

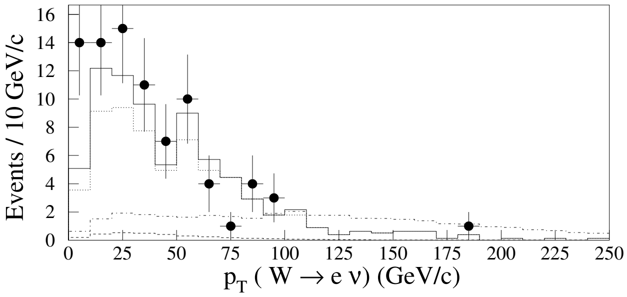

FIG. 2. p_T distributions of the $e\nu$ system: data (points), total background (solid), $W+\geq 2$ jets background (dotted), and Monte Carlo predictions of WW and WZ production with SM (dashed) and non-SM (dot–dashed, $\Delta\kappa_Z = \Delta\kappa_\gamma = 2$, $\lambda_Z = \lambda_\gamma = 1.5$) couplings.

We obtained limits on the coupling parameters using four different assumptions of how the parameters are related to each other (a–d, below). The 95% CL contour limits are shown as the inner curves in Fig. 3, along with the S–matrix unitarity limits, shown as the outer curves, which are obtained by evaluating all (i.e., $W\gamma$, WW and WZ) processes. The 95% CL limits on the axes are listed in Table II. Two Λ values are used, $\Lambda = 1.5$ TeV for (a), (b) and (c), and $\Lambda = 1.0$ TeV for (d). These are values used in other measurements [3,5]. For (d), the results obtained with $\Lambda = 1.5$ TeV violate the S–matrix unitarity limit (not shown).

TABLE II. 95% CL limits with various assumptions.

Assumptions	Λ (TeV)	Limits on axes
(a) $\Delta\kappa_\gamma = \Delta\kappa_Z$	1.5	$-0.9 < \Delta\kappa < 1.1$ $(\lambda = 0)$
$\lambda_\gamma = \lambda_Z$		$-0.6 < \lambda < 0.7$ $(\Delta\kappa = 0)$
(b) HISZ [17]	1.5	$-1.0 < \Delta\kappa_\gamma < 1.3$ $(\lambda_\gamma = 0)$
		$-0.6 < \lambda_\gamma < 0.7$ $(\Delta\kappa_\gamma = 0)$
(c) SM $WW\gamma$	1.5	$-1.1 < \Delta\kappa_Z < 1.3$ $(\lambda_Z = 0)$
		$-0.7 < \lambda_Z < 0.7$ $(\Delta\kappa_Z = 0)$
(d) SM WWZ	1.0	$-2.8 < \Delta\kappa_\gamma < 3.3$ $(\lambda_\gamma = 0)$
		$-2.5 < \lambda_\gamma < 2.6$ $(\Delta\kappa_\gamma = 0)$

In conclusion, we have searched for anomalous WW and WZ production in the $e\nu jjX$ decay mode, and set limits on the $WW\gamma$ and WWZ anomalous coupling parameters $\Delta\kappa$ and λ. The limits on λ are comparable to those measured using $W\gamma$ production, whereas those on $\Delta\kappa$ from this analysis are significantly better. The results with assumption (c) are unique to $WW(WZ)$ production since the WWZ couplings are not accessible with $W\gamma$ production. The limits on both $\Delta\kappa$ and λ are significantly tighter than those from the analysis using WW to dilepton decay, due to the additional WZ production mode here, and to the larger branching fractions of $W(Z)$ decaying to hadrons than that of W to $e\nu$ or $\mu\nu$ in the dilepton analysis.

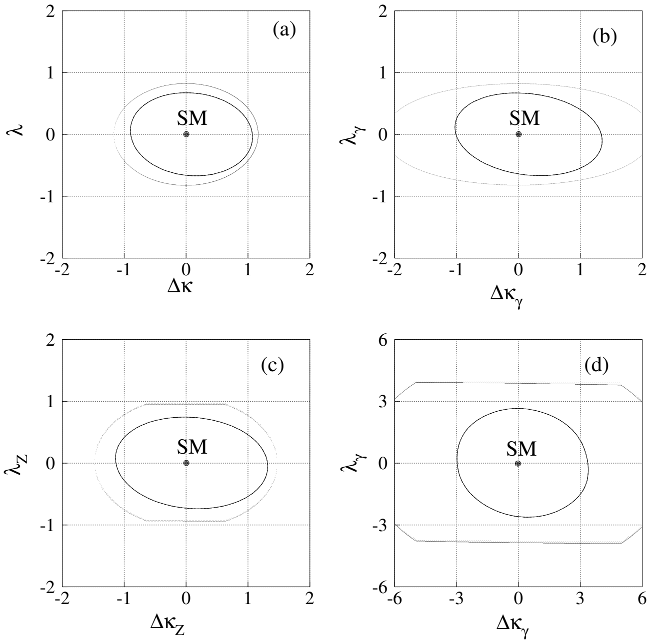

FIG. 3. Contour limits on anomalous coupling parameters at the 95% CL (inner curves) and limits from S–matrix unitarity (outer curves), assuming (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations [17]; (c) SM $WW\gamma$ couplings, and (d) SM WWZ couplings. $\Lambda = 1.5$ TeV is used for (a), (b) and (c); $\Lambda = 1.0$ TeV is used for (d). The SM prediction is $\Delta\kappa = 0, \lambda = 0$.

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[1] For WW and WZ production, see, for example, K. Hagiwara, J. Woodside and D. Zeppenfeld, Phys. Rev. D **41**, 2113 (1990); J. Ohnemus, Phys. Rev. D **44**, 1403 (1991).
[2] K. Hagiwara, R.D. Peccei, D. Zeppenfeld and K. Hikasa, Nucl. Phys. **B282**, 253 (1987).
[3] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **75**, 1034 (1995). For $W\gamma$ production with $\Lambda = 1.5$ TeV, DØ measures $-1.6 < \Delta\kappa < 1.8$ (with $\lambda = 0$) and $-0.6 < \lambda < 0.6$ (with $\Delta\kappa = 0$).
[4] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **75**, 1023 (1995). For $WW \to ll$ production and $\Lambda = 0.9$ TeV, DØ measures $-2.6 < \Delta\kappa < 2.8$ (with $\lambda = 0$) and $-2.1 < \lambda < 2.1$ (with $\Delta\kappa = 0$).
[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **75**, 1017 (1995). For $WW, WZ \to l\nu jj$ and $WZ \to jjll$ production and $\Lambda = 1.0$ TeV, CDF measures $-1.11 < \Delta\kappa < 1.27$ (with $\lambda = 0$) and $-0.81 < \lambda < 0.84$ (with $\Delta\kappa = 0$).
[6] DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods **A338**, 185 (1994).
[7] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. D **52**, 4877 (1995).
[8] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **75**, 1456 (1995).
[9] F. Paige and S. Protopopescu, BNL Report BNL38034, 1986 (unpublished), release V6.49.
[10] T. Sjöstrand, Computer Physics Commun. **82**, 74 (1994).
[11] F. Carminati *et al.*, "GEANT Users Guide," CERN Program Library, 1991 (unpublished).
[12] D. Zeppenfeld, private communication.
[13] W. Giele, E. Glover and D. Kosower, Nucl. Phys. **B403**, 633 (1993).
[14] Cross section and uncertainty are from E. Laenen, J. Smith and W.L. van Neerven, Phys. Lett. **B321**, 254 (1994).
[15] The Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994).
[16] C. Wendt, in the proceedings of the International Symposium on Vector Boson Self-Interactions, Los Angeles, CA, (February 1995), eds. U. Baur, S. Errede and T. Muller, p. 285.
[17] K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993). They parametrize the WWZ couplings in terms of the $WW\gamma$ couplings: $\Delta\kappa_Z = \frac{1}{2}\Delta\kappa_\gamma(1 - \tan^2\theta_W)$, $\Delta g_Z = \frac{1}{2}\Delta\kappa_\gamma / \cos^2\theta_W$ and $\lambda_Z = \lambda_\gamma$.