Limits on WWZ and $WW\gamma$ couplings from $p\bar{p} \rightarrow e\nu jjX$ events at $\sqrt{s} = 1.8$ TeV

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We present limits on anomalous WWZ and $WW\gamma$ couplings from a search for WW and WZ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We use $p\bar{p} \to e\nu jjX$ events recorded with the DØ detector at the Fermilab Tevatron Collider during the 1992–1995 run. The data sample corresponds to an integrated luminosity of 96.0 ± 5.1 pb^{-1}. Assuming identical WWZ and $WW\gamma$ coupling parameters, the 95% CL limits on the CP–conserving couplings are $-0.33 < \lambda < 0.36$ ($\Delta\kappa = 0$) and $-0.43 < \Delta\kappa < 0.59$ ($\lambda = 0$), for a form factor scale $\Lambda = 2.0$ TeV. Limits based on other assumptions are also presented.

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The vector boson trilinear couplings predicted by the non-Abelian gauge symmetry of the Standard Model (SM) can be measured directly in pair production processes such as $q\bar{q} \to W^+W^-$, $W^\pm\gamma$, $Z\gamma$, and $W^\pm Z$. Deviations from the SM couplings would signal new physics. Studies of such effects have been reported by the UA2 [1], CDF [2] and DØ [3–5] collaborations. In this letter we report on the measurement of WWV couplings (where $V = \gamma$ or Z) using the diboson production processes $p\bar{p} \to WWX \to e\nu jjX$ and $p\bar{p} \to WZX \to e\nu jjX$, where j represents a jet.

The Lorentz invariant Lagrangian which describes the $WW\gamma$ and WWZ interactions has fourteen independent coupling parameters [6], seven describing the $WW\gamma$ vertex and seven for the WWZ vertex. Assuming electromagnetic gauge invariance and CP conservation, the number of parameters is reduced to five: g_1^Z, κ_Z, κ_γ, λ_Z and λ_γ. In the SM at tree level, the coupling parameters have the values $\Delta g_1^Z (\equiv g_1^Z - 1) = 0$, $\Delta\kappa_Z (\equiv \kappa_Z - 1) = \Delta\kappa_\gamma (\equiv \kappa_\gamma - 1) = 0$, $\lambda_Z = \lambda_\gamma = 0$. The SM cross sections for $p\bar{p} \to W^+W^-X$ and $p\bar{p} \to W^\pm ZX$ production at the Tevatron, at $\sqrt{s} = 1.8$ TeV, are 9.5 pb and 2.7 pb [7] respectively.

Non-SM values of the coupling parameters would result in an increase of the production cross section, especially for large values of the transverse momentum of the W boson (p_T^W). Since tree level unitarity restricts the WWV couplings to their SM values at asymptotically high energies, each of the couplings must be modified by a form factor e.g. $\lambda_Z(\hat{s}) = \lambda_Z/(1+\hat{s}/\Lambda^2)^2$, where $\hat{s}$ is the square of the invariant mass of the WW or WZ system and Λ is the form-factor scale. We have used $\Lambda = 1.0$, 1.5 and 2.0 TeV.

The analysis reported here uses $p\bar{p} \to e\nu jjX$ events recorded with the DØ detector during the 1992–1993 and 1993–1995 Fermilab Tevatron Collider runs at $\sqrt{s} = 1.8$ TeV, corresponding to a total integrated luminosity of 96.0 ± 5.1 pb^{-1}. The DØ detector and data collection system are described elsewhere [8]. The basic elements of the trigger and reconstruction algorithms for jets, electrons, and neutrinos are given in Ref. [5]. The analysis of $e\nu jjX$ events from the 1992–1993 Tevatron Collider run (13.7 ± 0.7 pb^{-1}) was reported previously [4]. This letter focuses on the analysis of the 1993–1995 data set of 82.3 ± 4.4 pb^{-1} and gives the combined results for both analyses. Further details are available in Ref. [9].

The data sample was obtained with a trigger which required an isolated electromagnetic (EM) calorimeter cluster with transverse energy $E_T > 20$ GeV and missing transverse energy $\not\!\!E_T > 15$ GeV. The offline event selection required that the EM cluster have $|\eta| < 1.1$ in the central calorimeter or $1.5 < |\eta| < 2.5$ in an end calorimeter, where η is the pseudorapidity. Electrons were identified by requiring that the EM cluster pass the shower profile and tracking information criteria, as described in our earlier analysis [4]. The presence of a neutrino was inferred from the $\not\!\!E_T$, calculated from the vector sum of the E_T measured in each calorimeter tower. Jets were reconstructed using a cone algorithm with radius $\mathcal{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$. To remove spurious jets due to detector effects, this analysis used the same quality cuts as were used in Ref. [10]. Jets were required to be within $|\eta| < 2.5$. The jet energies were corrected for effects of jet energy scale calibration, out-of-cone showering, energy from the underlying event [11], and energy loss due to out-of-cone gluon radiation.

The WW/WZ candidates were selected by searching for events containing an isolated electron with high E_T^e (> 25 GeV), large $\not\!\!E_T$ (> 25 GeV) and at least two high E_T^j jets (> 20 GeV). The transverse mass of the electron and neutrino system was required to be consistent with a $W \to e\nu$ decay ($M_T^{e\nu} = [2E_T^e \not\!\!E_T (1 - \cos\phi^{e\nu})]^{1/2} > 40$ GeV/c^2, where $\phi^{e\nu}$ is the azimuthal angle between the electron and $\not\!\!E_T$ vector). The invariant mass (m^{jj}) of the two jet system (the largest invariant mass if there were more than two jets with $E_T^j > 20$ GeV in the event) was required to be $50 < m^{jj} < 110$ GeV/c^2, as expected for a $W \to jj$ or $Z \to jj$ decay. Monte Carlo studies showed that the dijet invariant mass resolution for signal events is 16 GeV/c^2. The transverse momentum of the two gauge bosons was required to be within $|p_T^{jj} - p_T^{e\nu}| < 40$ GeV/c, as expected for WW/WZ production.

There are two major sources of background to $WW/WZ \to e\nu jj$ production: (i) $W+ \geq 2$ jets with $W \to e\nu$; and (ii) QCD multijet events where one of the jets is misidentified as an electron and there is significant $\not\!\!E_T$ in the event due to mismeasurement. Other backgrounds such as: $t\bar{t}$ production with subsequent decay to $W^+bW^-\bar{b}$ followed by $W \to e\nu$; WW or WZ production with $W \to \tau\nu$ followed by $\tau \to e\nu\bar{\nu}$; $ZX \to eeX$, where one electron is mismeasured or not identified; and $ZX \to \tau\tau X$ with $\tau \to e\nu\bar{\nu}$, are negligible.

The $W+ \geq 2$ jets background was estimated using the VECBOS [12] event generator, with $Q^2 = (p_T^j)^2$, followed by parton fragmentation using the HERWIG [13] package and a detailed GEANT [14] based simulation of the detector. Normalization of the $W+ \geq 2$ jets background was determined by comparing the number of events expected from the VECBOS estimate to the number of candidate events outside the dijet mass window, after the multijet backgrounds had been subtracted. The systematic uncertainties in this background are due to the normalization and to the jet energy scale correction. The multijet background was estimated following the same procedure used in our previous analysis [4]. The background sample, which consisted of data events containing a jet satisfying the electron trigger selection but failing the electron identification, was normalized to the signal sample in the region $\not\!\!E_T < 15$ GeV where the actual WW/WZ contribution is negligible. The number of background events was then determined from this scaled background sample with the rest of the selection criteria applied [9]. The backgrounds from $t\bar{t} \rightarrow W^+bW^-\bar{b}$ and other minor sources were estimated using the ISAJET event generator [15] followed by detector simulation. Table I summarizes the background estimates and the total number of events seen. The number of observed events was consistent with the background estimates which dominate the SM WW/WZ signal.

The trigger and offline electron identification efficiencies were estimated using $Z \rightarrow ee$ events. The trigger efficiency was $(98.1 \pm 1.9)\%$ [3]. The electron identification efficiencies were found to be $(74.5 \pm 1.1)\%$ in the central calorimeter and $(61.9 \pm 1.1)\%$ in the end calorimeters. We studied the $W \rightarrow jj$ efficiency for the jet cone size $\mathcal{R} = 0.5$ using the ISAJET and PYTHIA [16] event generators followed by detector simulation. The selection criteria were applied to these samples and it was found that the efficiency was $\approx 50\%$ for $p_T^W < 250$ GeV/c and that this decreased significantly for $p_T^W > 250$ GeV/c due to merging of the two jets into one. The efficiencies obtained from ISAJET were used to estimate the detection efficiencies of the $WW(WZ)$ processes since they gave more conservative results.

The overall event selection efficiency was calculated using the leading order event generator of Ref. [17] to generate four-momenta for WW and WZ processes as a function of the coupling parameter values. A fast detector simulation was used to take into account the detector resolutions and efficiencies described above. Higher order QCD effects were approximated by a K–factor $= 1 + \frac{8}{9}\pi\alpha_s = 1.34$ [7] and a smearing of the transverse momentum of the diboson system according to the experimentally determined p_T^Z spectrum from the inclusive $Z \rightarrow ee$ sample. The total selection efficiencies for the detection of SM WW and WZ events were estimated to be [$14.7 \pm$ 0.2 (stat) $\pm$ 1.2 (syst)]% and [$14.6 \pm$ 0.4 (stat) $\pm$ 1.1 (syst)]%, respectively. The systematic uncertainty (8%) includes: electron trigger and selection efficiencies (1%); $\not{E}_T$ smearing and p_T of the WW/WZ diboson system (5%); difference between the ISAJET and PYTHIA programs for $W \rightarrow jj$ efficiency parametrization (5%); statistical uncertainty for $W \rightarrow jj$ efficiency parametrization (2%); and jet energy scale (3%).

TABLE I. Summary of signal and backgrounds.

	1992–1993	1993–1995
Luminosity	13.7 pb^{-1}	82.3 pb^{-1}
Backgrounds		
$W+ \geq 2$ jets	62.2±13.0	279.5±36.0
QCD Multijet	12.2±2.6	104.3±12.3
$t\bar{t} \rightarrow e\nu\ jjX$	0.9±0.1	3.7±1.3
Total Background	75.3±13.3	387.5±38.1
Data	84	399
SM WW+WZ prediction	3.2±0.6	17.5±3.0

The expected signal for WW plus WZ production with SM couplings is 20.7 ± 3.2 events based on the total integrated luminosity of 96.0 pb^{-1}. Figure 1 shows the $p_T^{e\nu}$ distributions for candidate events from 1993–1995 data, total background estimate plus SM expectations, and SM expectations for WW and WZ production, after all selection criteria have been applied. There is no clear difference between the observed $p_T^{e\nu}$ spectrum and that expected from background plus SM WW and WZ prediction.

Using the detection efficiencies for SM WW and WZ production and the background subtracted signal, and assuming the SM ratio of cross sections for WW and WZ production, we can set an upper limit at the 95% CL on the cross section $\sigma(p\bar{p} \rightarrow W^+W^-X)$ of 76 pb.

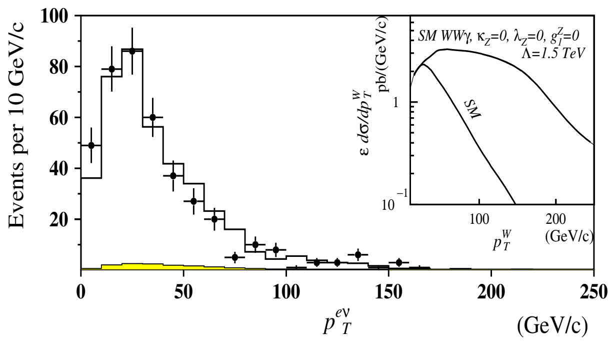

FIG. 1. p_T distributions of the $e\nu$ system for the 1993–1995 data set. The points with error bars represent the data. The solid histogram is the total background estimate plus the SM Monte Carlo predictions of WW and WZ production (shown as shaded histogram). The inset shows the predicted $d\sigma/dp_T^W$, folded with the detection efficiencies, for SM $WW\gamma$ and WWZ couplings (lower curve), and for SM $WW\gamma$ and the indicated anomalous WWZ couplings (upper curve).

Since we observed no excess of high $p_T^{e\nu}$ events, large deviations from the SM trilinear coupling values are excluded. Limits on the anomalous coupling parameters were set by performing a binned likelihood fit to the observed $p_T^{e\nu}$ spectrum with the Monte Carlo signal prediction plus the estimated background. Unequal width bins were used to evenly distribute the observed events, especially those at the end of the spectrum. In each $p_T^{e\nu}$ bin for a given set of anomalous coupling parameters, we calculated the probability for the sum of the background estimate and Monte Carlo WW/WZ prediction to fluctuate to the observed number of events. The limits on the anomalous coupling parameters are from a combined likelihood fit to both data sets. The uncertainties in the background estimates, efficiencies, integrated luminosity, and higher order QCD corrections to the signal were convoluted with Gaussian distributions into the likelihood function. Uncertainties common to both analyses, e.g. theoretical uncertainties, were convoluted only once.

In Fig. 2, bounds on four pairs of coupling parameters are shown using $\Lambda = 1.5$ TeV. In each case all other couplings are fixed to their SM values. The one- and two-degree-of-freedom 95% CL contour limits (corresponding to likelihood function values 1.92 and 3.00 units below the maximum, respectively) are shown as the inner curves, along with the S-matrix unitarity limits, shown as the outermost curves, which are obtained by evaluating all (i.e. WW, $W\gamma$, and WZ) processes. Figure 2(a) shows the contour limits when coupling parameters for $WW\gamma$ are assumed to be equal to those for WWZ. Figure 2(b) shows contour limits assuming HISZ relations [18]. In Fig. 2(c) and 2(d) SM $WW\gamma$ couplings are assumed and the coupling limits for WWZ are shown.

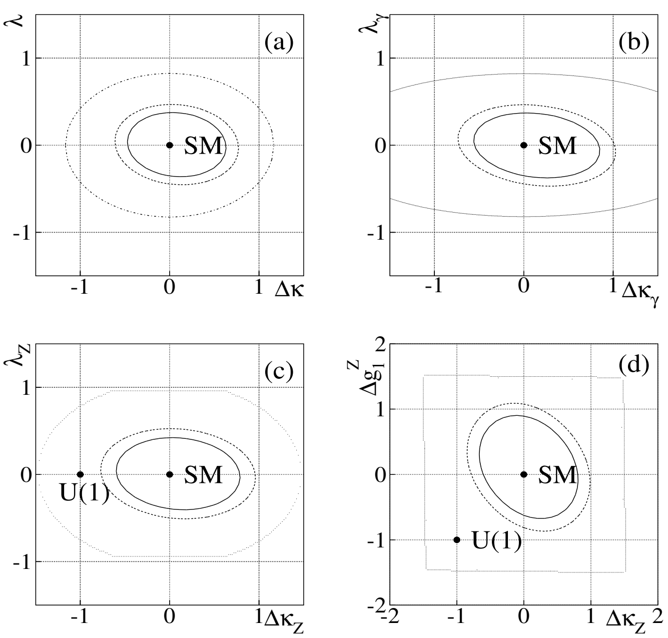

FIG. 2. Limits on CP–conserving anomalous couplings parameters: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; (b) HISZ relations; (c) and (d) SM $WW\gamma$ couplings. The inner and middle curves represent 95% CL one- and two-degree-of-freedom exclusion contours, respectively. The outermost curves show S–matrix unitarity bounds. $\Lambda = 1.5$ TeV is used for all four cases. The SM prediction is $\Delta\kappa = 0, \lambda = 0$, $\Delta g_1^Z = 0$.

TABLE II. Axis limits at the 95% CL with various assumptions and three different Λ values.

Couplings / Λ(TeV)		1.0	1.5	2.0
(i)	$\lambda_\gamma = \lambda_Z$	$-0.42, 0.45$	$-0.36, 0.39$	$-0.33, 0.36$
	$\Delta\kappa_\gamma = \Delta\kappa_Z$	$-0.55, 0.79$	$-0.47, 0.63$	$-0.43, 0.59$
(ii)	λ_γ (HISZ)	$-0.42, 0.45$	$-0.36, 0.38$	$-0.34, 0.36$
	$\Delta\kappa_\gamma$ (HISZ)	$-0.69, 1.04$	$-0.56, 0.85$	$-0.53, 0.78$
(iii)	λ_Z (SM $WW\gamma$)	$-0.47, 0.51$	$-0.40, 0.43$	$-0.37, 0.40$
	$\Delta\kappa_Z$ (SM $WW\gamma$)	$-0.74, 0.99$	$-0.60, 0.79$	$-0.54, 0.72$
	Δg_1^Z (SM $WW\gamma$)	$-0.75, 1.06$	$-0.64, 0.89$	$-0.60, 0.81$
(iv)	λ_γ (SM WWZ)	$-1.28, 1.33$	$-1.21, 1.25$	
	$\Delta\kappa_\gamma$ (SM WWZ)	$-1.60, 2.03$	$-1.38, 1.70$	

When SM $WW\gamma$ couplings are assumed, the U(1) point ($\kappa_Z = 0$, $\lambda_Z = 0$, $g_1^Z = 0$) is excluded at the 99% CL. This is direct evidence for the existence of the WWZ couplings.

Table II lists the 95% CL axis limits for three different values of Λ and four assumptions: (i) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; (ii) HISZ relations; (iii) SM $WW\gamma$ couplings; and (iv) SM WWZ couplings. The results with the SM $WW\gamma$ assumption are unique to WW/WZ production since the WWZ couplings are not accessible with $W\gamma$ production. The results indicate that this analysis is more sensitive to WWZ couplings than to $WW\gamma$ ones as expected from the larger overall couplings for WWZ than $WW\gamma$ [6]. The dependence of the coupling parameters on Λ is clearly seen. Tighter limits are obtained when a larger value for Λ is used. When SM WWZ couplings are assumed, our limits on λ_γ and $\Delta\kappa_\gamma$ with $\Lambda = 2.0$ TeV are not tight enough to lie within the S-matrix unitarity limit.

In conclusion, we have presented limits on anomalous WWZ and $WW\gamma$ coupling parameters which are the most stringent to date. They are significantly tighter than those from the analyses of the 1992–1993 data set [2,4], and significantly better on $\Delta\kappa$ (but comparable on λ) to those measured using $W\gamma$ production with the 1992–1995 data set [3].

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