Limits on $WW\gamma$ and WWZ Couplings from W Boson Pair Production

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Abstract

The results of a search for W boson pair production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with subsequent decay to $e\mu$, ee, and $\mu\mu$ channels are presented. Five candidate events are observed with an expected background of 3.1 ± 0.4 events for an integrated luminosity of approximately 97 pb^{-1}. Limits on the anomalous couplings are obtained from a maximum likelihood fit of the E_T spectra of the leptons in the candidate events. Assuming identical $WW\gamma$ and WWZ couplings, the 95% C.L. limits are $-0.62 < \Delta\kappa < 0.77$ ($\lambda = 0$) and $-0.53 < \lambda < 0.56$ ($\Delta\kappa = 0$) for a form factor scale $\Lambda = 1.5$ TeV.

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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). The trilinear gauge boson coupling strengths can be measured directly by studying gauge boson pair production. Hadron collider experiments have established the electroweak coupling of the W boson to the photon [1] and the existence of the coupling between the W boson and the Z boson [2,3], and have placed constraints on anomalous $WW\gamma$ and WWZ couplings [4–8]. Measurements of the couplings also have been reported by the LEP collaborations [9].

The $WW\gamma$ and WWZ vertices can be described by a general effective Lagrangian [10] 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. Electromagnetic gauge invariance requires that $g_1^\gamma = 1$. The effective Lagrangian becomes that of the SM when $g_1^\gamma = g_1^Z = 1$, $\kappa_V = 1 (\Delta\kappa_V \equiv \kappa_V - 1 = 0)$, and $\lambda_V = 0$. In order to preserve unitarity at high energies, the anomalous couplings are modified by form factors with a scale Λ (e.g. $\lambda_V(\hat{s}) = \lambda_V(0)/(1 + \hat{s}/\Lambda^2)^2$). Limits on these coupling strengths 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 $\lambda_\gamma = \lambda_Z$), leaving two independent couplings to be determined. In another approach [11], the anomalous couplings are formulated in a framework that explicitly respects the $SU(2) \times U(1)$ gauge invariance, but contains more general terms than those of Ref. [10]. Comparison of the two formalisms leads to simple equations (HISZ relations) that relate anomalous couplings in the general effective Lagrangian.

In this paper we present the results of a search for $p\bar{p} \rightarrow WW + X \rightarrow \ell\bar{\ell}'\bar{\nu}\nu' + X$ at $\sqrt{s} = 1.8$ TeV, where $\ell, \ell' = e$ or μ. Limits on anomalous $WW\gamma$ and WWZ couplings are obtained for both the equal couplings and the HISZ relations by a maximum likelihood fit of the observed two-dimensional spectra of lepton transverse energy E_T. This method provides tighter limits on anomalous couplings than those from the measurement of the cross section [6,7]. The $WW \rightarrow \ell\bar{\ell}'\bar{\nu}\nu'$ channel has significantly less background, albeit with a smaller branching ratio, and is more sensitive to WW production with the SM couplings than the $WW/WZ \rightarrow \ell\nu jj/\ell\bar{\ell}jj$ channel. Therefore, limits obtained from this analysis are complementary to those from the $WW/WZ \rightarrow \ell\nu jj/\ell\bar{\ell}jj$ analyses [2,3].

The data sample corresponds to an integrated luminosity of approximately 97 pb^{-1} collected with the DØ detector during the 1992–93 and 1993–1995 Tevatron collider runs at Fermilab. The results based on the 1992–1993 data sample of approximately 14 pb^{-1} were previously reported [6,8]. This paper describes the analysis of the 1993–1995 data sample and gives the combined results from the two analyses.

The DØ detector [12] consists of three major components: the calorimeter, tracking, and muon systems. A hermetic, compensating, uranium-liquid argon sampling calorimeter with fine transverse and longitudinal segmentation in projective towers measures energy out to $|\eta| \sim 4.0$, where η is the pseudorapidity. The central and forward drift chambers are used to identify charged tracks for $|\eta| \leq 3.2$. There is no central magnetic field. Muons in the central region are identified and their momenta measured with three layers of proportional drift tubes (PDT's), one inside and two outside of magnetized iron toroids, providing coverage for $|\eta| \leq 1.7$. In addition, scintillation counters mounted on the outer layer of PDT's provide time information for muon identification and cosmic ray rejection.

Event samples are obtained from triggers with the signature of leptonic W boson decays. The ee and $e\mu$ samples are selected from events passing a trigger which requires an electromagnetic cluster with $E_T > 20$ GeV and missing transverse energy $\not\!\!E_T > 15$ GeV. The integrated luminosity for this sample is 82.3 ± 4.4 pb^{-1}. The $\mu\mu$ sample is selected from events passing a trigger which requires at least one muon track in the fiducial region of $|\eta| \leq 1.0$ with $p_T > 15$ GeV/c, energy deposition in the calorimeter consistent with the passage of a muon, and no hits due to cosmic ray muons in the scintillator located outside of the muon chambers. The integrated luminosity for this sample is 65.2 ± 3.5 pb^{-1}.

Isolated electrons are identified using a likelihood function formed from four variables: the electromagnetic energy fraction of the calorimeter cluster, the χ^2 of longitudinal and transverse shower shapes compared to test-beam and Monte Carlo electrons, the ionization energy deposition (dE/dx) in the central tracking detector associated with the matching track, and the distance between the projected track position and the centroid of the energy cluster at the calorimeter. This likelihood function is used to discriminate between electrons and photon conversions, photon showers overlapped with a charged hadron track, and hadronic showers with large electromagnetic content. For a given identification efficiency, this method provides a background rejection 2-3 times higher than a method that places requirements on individual variables [13]. In the central region, $|\eta| \leq 1.1$, the electron detection efficiency is $(59.9\pm0.8)\%$; in the forward region, $1.5 \leq |\eta| \leq 2.5$, it is $(47.1\pm1.4)\%$.

Muons are required to have associated hits in at least two of the three layers of the muon system. They must be isolated from jets ($\Delta\mathcal{R}(\mu, \text{jet}) > 0.5$ for $E_T^{\text{jet}} > 10$GeV, where $\Delta\mathcal{R}(\mu, \text{jet})$ is the separation between muon and jet in $\eta - \phi$ space) and have energy deposition in the calorimeter consistent with a minimum ionizing particle. The muon track is required to point to the primary event vertex within 25 cm in the plane transverse to the beam and to occur at a time, as measured by the PDT's, within 200 ns of the beam crossing. The muon detection efficiency is $(70.1 \pm 3.1)\%$ within the fiducial acceptance of $|\eta| \leq 1.0$ employed in this analysis.

The ee candidate events are selected by requiring the leading electron to have $E_T \geq 25$ GeV and a second electron to have $E_T \geq 20$ GeV. The $\not\!\!E_T$ is required to exceed 25 GeV. Background from events with high-p_T Z bosons is reduced by removing events with dielectron invariant mass within 15 GeV/c^2 of the Z boson mass. The $e\mu$ candidate events are selected by requiring an electron with $E_T \geq 25$ GeV and a muon with $p_T \geq 15$ GeV/c. We require $\not\!\!E_T^{\text{cal}} \geq 25$ GeV (where $\not\!\!E_T^{\text{cal}}$ is $\not\!\!E_T$ calculated using only the calorimeter and is not affected by the muon momentum resolution) and $\not\!\!E_T \geq 20$ GeV. An isolation condition, $\Delta\mathcal{R}(e, \mu) \geq 0.5$, where $\Delta\mathcal{R}(e, \mu)$ is the separation between electron and muon in η-ϕ space, is applied to remove background from cosmic ray muons accompanied by a bremsstrahlung photon. The $\mu\mu$ candidate events are selected by requiring a leading muon with $p_T \geq 25$ GeV/c and a second muon with $p_T \geq 20$ GeV/c. The projection of $\not\!\!E_T$ onto the bisector of the muon tracks in the transverse plane is required to exceed 30 GeV in order to remove background from Z boson production. This is less sensitive to the muon momentum resolution than a dimuon invariant mass requirement.

Additional cuts are applied similarly to all three channels. To remove background from $Z \to \tau\tau$, and from $b\bar{b}$ production in the $\mu\mu$ channel, the transverse opening angle $\Delta\phi_\ell$ between one charged lepton ℓ and $\not\!\!E_T$ is required to be less than 160°. This cut is applied to the second-leading electron in the ee channel, the muon in the $e\mu$ channel, and the leading muon in the $\mu\mu$ channel. In addition, for the ee and $e\mu$ channels, $\Delta\phi_\ell$ is required to exceed 20°, and both $\Delta\phi_\ell$ requirements are removed if $\not\!\!E_T > 50$ GeV. Also, to reduce background in all three channels from $t\bar{t}$ production, the hadronic E_T in the event, $\vec{E}_T^{\rm had} \equiv -(\vec{E}_T^{\ell 1} + \vec{E}_T^{\ell 2} + \vec{\not\!\!E}_T)$, is required to satisfy $E_T^{\rm had} < 40$ GeV. After imposing these selection criteria, one ee candidate, two $e\mu$ candidates, and one $\mu\mu$ candidate remain.

The detection efficiencies for W boson pair production with SM and anomalous couplings are determined using a fast Monte Carlo program (the Monte Carlo event generator of Ref. [14] plus a parametric detector simulation). The detection efficiencies for SM W boson pair production are also calculated using the PYTHIA [15] event generator followed by a detailed GEANT [16] simulation of the DØ detector and are found to agree with those determined from the fast Monte Carlo. Trigger and particle identification efficiencies are determined from the data. The trigger efficiency for the ee and $e\mu$ data samples is $(99^{+1}_{-3})\%$. For the $\mu\mu$ sample, the trigger efficiency is $(68.7 \pm 5.8)\%$. Table I shows the detection efficiencies for SM W boson pair production events and the number of expected events based on a cross section of 9.4 pb [17]. The systematic uncertainty in the detection efficiency comes from electron (2.2%) and muon (7.5%) identification, electron (2.0%) and muon (8.5%) trigger efficiencies, and the difference between the detection efficiencies estimated with the two Monte Carlo methods (5%). Uncertainty due to the choice of parton distribution function and evolution scale (5%) is included in the uncertainty on the number of expected events.

Backgrounds due to Drell-Yan dileptons, $W\gamma$, $t\bar{t}$, and Z boson production are estimated using the PYTHIA, ISAJET [18] and HERWIG [19] Monte Carlo event generators, followed by the detailed GEANT simulation of the DØ detector. Backgrounds due to high-p_T $Z \to ee$ and $\mu\mu$ events are studied using a Monte Carlo event generator based on the theoretical model of Ref. [20] and the parametric detector simulation. Backgrounds from multijet and W + jet events with a jet misidentified as an electron and with heavy quark production of isolated muons are estimated from the data. The probabilities for a jet to be misidentified as an electron and for a jet to be accompanied by a muon that satisfies the isolation criterion are measured from a large sample of events passing jet triggers. Events with large $\not\!\!E_T$ are rejected from this sample to remove W+jets events. For electrons, the misidentification probability is found to be a slowly rising linear function of jet E_T (3.7×10^{-5} at 20 GeV, 1.9×10^{-4} at 100 GeV in the central region; and 3.5×10^{-5} at 20 GeV, 1.8×10^{-4} at 100 GeV in the forward region), while for muons it is found to be constant (1.5×10^{-5} for the $e\mu$ sample and 1.5×10^{-4} for the $\mu\mu$ sample). The background estimates are summarized in Table II. Systematic uncertainties include those listed above as well as the uncertainty on the production cross section of the background processes.

The number of candidate events, four in the 1993–1995 data sample (five when the 1992–1993 data sample with one ee candidate and 0.6 ± 0.1 background events is included), is consistent with an expected SM WW signal of 1.5 ± 0.1 (1.9 ± 0.1) events plus an estimated background of 2.5 ± 0.4 (3.1 ± 0.4) events. We have studied the stability of the results by relaxing some of the event selection requirements, e.g. $E_T^{\rm had}$ and dielectron invariant mass criteria. The increases in the numbers of candidate and background events are found to be consistent with the expectations. An upper limit on the W boson pair production cross section is calculated from the number of the candidate events and the estimated background events using the Poisson-distributed number of events convoluted with Gaussian uncertainties on the detection efficiencies, background, and luminosity. For SM W boson pair production, the upper limit for the cross section is 37.1 pb at the 95% C.L. using the

1992–1993 and 1993–1995 data samples. The probability that the observed number of events correspond to a fluctuation of the background, with no signal, is 20.6%.

By studying E_T spectra of leptons from W boson pair candidates, limits can be obtained on the anomalous $WW\gamma$ and WWZ couplings. Use of this kinematic information provides significantly tighter constraints on anomalous couplings than those from the measurement of the cross section (the method used in previous $WW \to \ell\bar{\ell}'\bar{\nu}\nu'$ analyses [6,7]), since the predicted increase in the gauge boson pair production cross section with anomalous couplings is greater at higher gauge boson p_T. A binned maximum likelihood fit is performed to the measured spectra of E_T of the two leptons in the event. Two-dimensional bins in E_T of one lepton versus E_T of the other lepton are used in order to take into account the correlation between the two leptons in the event. The binnings used in the fit are shown in Table III. The probability for the sum of the background estimate and Monte Carlo WW signal prediction to fluctuate to the observed number of events is calculated in each bin for a given set of anomalous couplings. The uncertainties on the background estimates, efficiencies, integrated luminosity, and theoretical prediction of the WW production cross section are convoluted with Gaussian distributions into the likelihood function. The likelihood functions are calculated for the 1992–1993 and 1993–1995 data samples separately and are combined taking into account correlated uncertainties, such as theoretical uncertainties.

The WW production process involves the $WW\gamma$ and WWZ couplings, unlike the $W\gamma$ production process which depends only on the $WW\gamma$ couplings. Limits on anomalous couplings are obtained using two assumptions on the relationship between the $WW\gamma$ and WWZ couplings. Figure 1 shows bounds on anomalous couplings from this analysis and from the unitarity condition [14,21] using $\Lambda = 1.5$ TeV. In Fig. 1(a), the values for $\Delta\kappa$ and λ are assumed to be equal for the $WW\gamma$ and WWZ couplings. Limits at the 95% C.L., when λ or $\Delta\kappa$ is set to zero, are:

$$-0.62 < \Delta\kappa < 0.77 \ (\lambda = 0);$$
$$-0.53 < \lambda < 0.56 \ (\Delta\kappa = 0)$$

In Fig. 1(b), the HISZ relations [11] are used. Limits at the 95% C.L. using the HISZ relations are:

$$-0.92 < \Delta\kappa_\gamma < 1.20 \ (\lambda_\gamma = 0);$$
$$-0.53 < \lambda_\gamma < 0.56 \ (\Delta\kappa_\gamma = 0)$$

The innermost curve is the 95% C.L. contour when only one coupling is treated as a free parameter (e.g., limits on the axes) while the middle curve is the 95% C.L. contour when both of the couplings are free parameters. All of the limits obtained in this analysis are comparable to those obtained from the analysis of $WW/WZ \to e\nu jj$ events [3].

In summary, a search for $WW \to \ell\bar{\ell}'\bar{\nu}\nu'$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is performed using the 1992–1993 and 1993–1995 data samples. In approximately 97 pb^{-1} of data, five candidate events are found with an estimated background of 3.1 ± 0.4 events. From the standard model, 1.9 ± 0.1 events are expected. The number of observed events is consistent with the standard model prediction plus background estimate. The 95% C.L. limits on the anomalous couplings $-0.62 < \Delta\kappa < 0.77$ ($\lambda = 0$) and $-0.53 < \lambda < 0.56$ ($\Delta\kappa = 0$) are obtained from a binned maximum likelihood fit of the E_T spectra of leptons, assuming equal $WW\gamma$ and WWZ couplings.

FIGURES

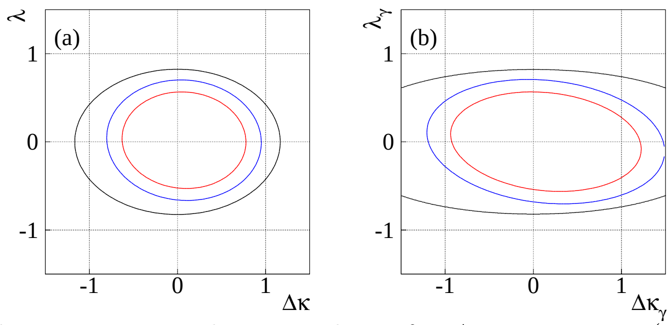

FIG. 1. Contour limits on anomalous couplings for $\Lambda = 1.5$ TeV: (a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda \equiv \lambda_\gamma = \lambda_Z$; and (b) HISZ relations. The innermost and middle curves are 95% C.L. one- and two-degree of freedom exclusion contours from the fit of the E_T spectra of leptons, respectively. The outermost curve is the constraint from the unitarity condition. Monte Carlo statistics limit the accuracy of the contours to ± 0.01.

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TABLES

TABLE I. Detection efficiencies and SM signal event expectations for the 1993–1995 data sample. The uncertainties include both statistical and systematic contributions.

Channel	ee	$e\mu$	$\mu\mu$
Detection Efficiency (%)	6.03 ± 0.36	4.76 ± 0.49	1.19 ± 0.18
SM Expectation (events)	0.52 ± 0.04	0.86 ± 0.10	0.09 ± 0.01

TABLE II. Summary of backgrounds and candidates for the 1993–1995 data sample. The units are number of events in the data sample. The uncertainties include both statistical and systematic contributions.

	ee	$e\mu$	$\mu\mu$
Background:			
$Z \to ee$ or $\mu\mu$	0.27 ± 0.06	–	0.39 ± 0.09
$Z \to \tau\tau$	0.10 ± 0.07	0.21 ± 0.08	$< 10^{-3}$
Drell-Yan dileptons	0.03 ± 0.04	–	$< 10^{-3}$
$W\gamma$	0.18 ± 0.07	0.35 ± 0.14	–
$t\bar{t}$	0.13 ± 0.05	0.18 ± 0.06	0.02 ± 0.01
multijets/W + jets	0.20 ± 0.14	0.43 ± 0.28	0.03 ± 0.01
Total background	0.91 ± 0.19	1.17 ± 0.33	0.44 ± 0.09
Data	1	2	1

TABLE III. The binnings used in the maximum likelihood fit to set limits on the anomalous couplings and the numbers of candidate events (background estimate) for the 1992–1993 and 1993–1995 data samples.

	ee channel (96.6 ± 4.5 pb^{-1})	
$E_T^{e1} \setminus E_T^{e2}$	$20 - 40$ (GeV)	$40 - 500$ (GeV)
$25 - 40$ (GeV)	2 (0.50 ± 0.10)	–
$40 - 500$ (GeV)	0 (0.35 ± 0.07)	0 (0.27 ± 0.06)
	$e\mu$ channel (96.2 ± 4.5 pb^{-1})	
$E_T^{e} \setminus E_T^{\mu}$	$15 - 40$ (GeV)	$40 - 500$ (GeV)
$25 - 50$ (GeV)	2 (0.95 ± 0.27)	0 (0.16 ± 0.05)
$50 - 500$ (GeV)	0 (0.16 ± 0.05)	0 (0.16 ± 0.05)
	$\mu\mu$ channel (77.4 ± 3.6 pb^{-1})	
$E_T^{\mu1} \setminus E_T^{\mu2}$	$20 - 40$ (GeV)	$40 - 500$ (GeV)
$25 - 40$ (GeV)	1 (0.08 ± 0.02)	–
$40 - 500$ (GeV)	0 (0.18 ± 0.04)	0 (0.26 ± 0.05)

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