Search for Anomalous $WW$ and $WZ$ production at DØ*

DØ Collaboration

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Abstract

We present a preliminary result from a search for anomalous $WW$ and $WZ$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using $p\bar{p} \rightarrow e\nu jj$ events observed during the 1992–1993 run of the Fermilab Tevatron collider. A fit to the $p_T$ spectrum of $W(e\nu)$ yields direct limits on the CP–conserving anomalous $WW\gamma$ and $WWZ$ coupling parameters of $-0.89 < \Delta\kappa < 1.07$ ($\lambda = 0$) and $-0.66 < \lambda < 0.67$ ($\Delta\kappa = 0$) at the 95% confidence level, assuming that the $WWZ$ coupling parameters are equal to the $WW\gamma$ coupling parameters, and a form factor scale $\Lambda = 1.5$ TeV.

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E. Won, D.R. Wood, H. Xu, R. Yamada, P. Yamin, C. Yanagisawa, J. Yang, T. Yasuda, C. Yoshikawa, S. Youssef, J. Yu, Y. Yu, Y. Zhang, Y.H. Zhou, Q. Zhu, Y.S. Zhu, Z.H. Zhu, D. Zieminska, A. Zieminski, and A. Zylberstejn

1 Universidad de los Andes, Bogotá, Colombia
2 University of Arizona, Tucson, Arizona 85721
3 Brookhaven National Laboratory, Upton, New York 11973
4 Brown University, Providence, Rhode Island 02912
5 University of California, Davis, California 95616
6 University of California, Irvine, California 92717
7 University of California, Riverside, California 92521
8 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
9 CINVESTAV, Mexico City, Mexico
10 Columbia University, New York, New York 10027
11 Delhi University, Delhi, India 110007
12 Fermi National Accelerator Laboratory, Batavia, Illinois 60510
13 Florida State University, Tallahassee, Florida 32306
14 University of Hawaii, Honolulu, Hawaii 96822
15 University of Illinois at Chicago, Chicago, Illinois 60607
16 Indiana University, Bloomington, Indiana 47405
17 Iowa State University, Ames, Iowa 50011
18 Korea University, Seoul, Korea
19 Kyungsung University, Pusan, Korea
20 Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720
21 University of Maryland, College Park, Maryland 20742
22 University of Michigan, Ann Arbor, Michigan 48109
23 Michigan State University, East Lansing, Michigan 48824
24 Moscow State University, Moscow, Russia
The self-interaction of electroweak gauge bosons is a direct consequence of the non-Abelian gauge theory of the Standard Model (SM) and can be tested through study of gauge boson pair ($W \gamma$, $Z \gamma$, $WW$ and $WZ$) production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [1]. The self-interaction coupling parameters are given precisely in the SM. Any deviation of the parameters from the SM values signals physics beyond the SM. Figure 1 shows leading order Feynman diagrams of $q\bar{q} \rightarrow WW$ and $q\bar{q}' \rightarrow WZ$ processes. The $WW$ production process depends strongly on the $WW\gamma$ and $WWZ$ coupling parameters due to destructive interference between contributing amplitudes. This interference prevents the SM $WW$ cross...
section from violating unitarity at high energies. The SM predicts the production cross sections for $\bar{p}p \rightarrow W^+W^-$ and $\bar{p}p \rightarrow W^\pm Z$ at $\sqrt{s} = 1.8$ TeV to be 8.4 pb and 2.5 pb, respectively \cite{2}. Based on a formalism developed by Hagiwara et. al \cite{3}, the $WW\gamma$ and $WWZ$ interactions beyond the SM can be parametrized by four independent dimensionless coupling parameters $\Delta\kappa_\gamma$ and $\lambda_\gamma$ for the $WW\gamma$ vertex and $\Delta\kappa_Z$ and $\lambda_Z$ for the $WWZ$ vertex. For the SM, $\Delta\kappa_\gamma = \lambda_\gamma = \Delta\kappa_Z = \lambda_Z = 0$. Non-zero coupling parameters result in a dramatic increase of the production cross section and an enhancement in the transverse momentum ($p_T^W$) spectrum of the $W$ boson in the high $p_T$ region as shown in Fig. 2. Thus, a study of the $p_T^W$ spectrum of $WW$ production leads to a sensitive test of the $WW\gamma$ and $WWZ$ couplings. Similarly, the $p_T^W$ spectrum of $WZ$ production provides a direct test of the $WWZ$ coupling.

The DØ collaboration has previously reported limits on anomalous trilinear gauge boson couplings from three processes using the data from the 1992–93 Tevatron collider run: the $WW\gamma$ coupling based on a measurement of $W\gamma$ production \cite{4}, $WWZ$ and $WW\gamma$ couplings from a search for $W$ boson pair production in dilepton decay modes \cite{5}, and $ZZ\gamma$ and $Z\gamma\gamma$ couplings from a measurement of $Z\gamma$ production \cite{6}. In this report we present a new, independent determination of limits on the anomalous $WW\gamma$ and $WWZ$ couplings obtained from a search for $\bar{p}p \rightarrow WW + X$ followed by $W \rightarrow \ell\nu$ and $W \rightarrow jj$, where $j$ represents a jet, and $\bar{p}p \rightarrow WZ + X$ followed by $W \rightarrow \ell\nu$ and $Z \rightarrow jj$, using the data from the 1992–1993 run, corresponding to an integrated luminosity of $13.7 \pm 0.7$ pb$^{-1}$. In this decay mode, $WZ$ events are indistinguishable from $WW$ events\cite{2}. The CDF collaboration has reported a similar measurement \cite{7}.

The $WW, WZ \rightarrow \ell\nu jj$ candidates were selected by searching for events containing a

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1In this paper we only consider CP–conserving couplings.

2 The SM predicts $\sigma \cdot B(\bar{p}p \rightarrow W^+W^- \rightarrow e^\pm\nu jj) = 1.23$ pb and $\sigma \cdot B(\bar{p}p \rightarrow W^\pm Z \rightarrow e^\pm\nu jj) = 0.19$ pb.
$W \rightarrow e\nu$ decay and two jets consistent with $W \rightarrow jj$ or $Z \rightarrow jj$. The data sample was obtained with a single electron trigger: an isolated electromagnetic (EM) cluster with transverse energy $E_T^e > 20$ GeV. This EM cluster was required to be within the fiducial region of the calorimeter $|\eta| \leq 1.1$ in the central calorimeter, or $1.5 \leq |\eta| \leq 2.5$ in the end calorimeters. Here $\eta$ is the pseudorapidity defined as $\eta = -\ln(\tan(\theta/2))$, $\theta$ being the polar angle with respect to the beam axis. The electron cluster had to have (i) a ratio of EM energy to the total shower energy greater than 0.9; (ii) lateral and longitudinal shower shape consistent with an electron shower; (iii) the isolation variable of the cluster less than 0.1, where isolation is defined as $I = (E(0.4) - EM(0.2))/EM(0.2)$, and $E(0.4)$ is the total calorimeter energy inside a cone of radius $R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$, and $EM(0.2)$ is the EM energy inside a cone of 0.2; and (iv) a matching track in the drift chambers. The $W \rightarrow e\nu$ decay was identified by an isolated electron with $E_T^e > 25$ GeV and missing transverse energy $E_T^\miss > 40$ GeV/c$^2$.

Jets were reconstructed by applying a cone algorithm with a radius $R = 0.3$ to the calorimeter hits. This small cone size minimized the probability for two jets from the $W(Z)$ boson to merge into one cluster in the calorimeter, in particular, in the high $p_T$ region. The jets were required to be within $|\eta| < 2.5$ and energy corrections including that for out-of-cone gluon radiation were applied. We required that a candidate event contain at least two jets with $E_T^j > 20$ GeV and that dijet invariant mass (the largest invariant mass if more than two jets with $E_T^j > 20$ GeV in the event) satisfy $50 < m_{jj} < 110$ GeV/c$^2$, consistent with $W$ and $Z$ masses. The above selection criteria yielded 84 candidate events.

The background estimate, summarized in Table 1, includes contributions from: QCD production of $W + \geq 2j$; QCD multijet events, where a jet was misidentified as an electron; $t\bar{t} \rightarrow W^+W^-bb \rightarrow e\nu jj X$; $WW$ with $W \rightarrow \tau\nu$ followed by $\tau \rightarrow e\nu\bar{\nu}$; and $ZX \rightarrow eeX$, where one electron was lost. The multijet background was estimated from the data by measuring the $E_T^\miss$ distribution of a background-dominated sample, obtained by selecting events containing an EM cluster which failed at least one of the electron quality requirements (isolation, shower shape and track-match). We extrapolated this $E_T^\miss$ distribution into the
signal region ($E_T > 25$ GeV) by normalizing the number of events in the background sample to that in the candidate sample (without the $E_T$ requirement imposed) in the region of small $E_T$ ($0 < E_T < 15$ GeV). We measured the total number of multijet background events to be $12.2 \pm 2.6$. The $W^+ \geq 2j$ background was estimated using the VECBOS [9] Monte Carlo followed by parton fragmentation using the ISAJET [10] program and a full detector simulation based on the GEANT program [11]. Using the dijet invariant mass distributions of the VECBOS sample and the observed $Wjj$ sample after subtracting the contribution from the multijet events, we normalized the number of VECBOS $W^+ \geq 2j$ events to the number of observed $Wjj$ events outside of the signal region $50 < m_{jj} < 110$ GeV/$c^2$. This yielded the total number of $W^+ \geq 2j$ background events (in the signal region) as $62.2 \pm 13.0$, where the uncertainty was due to the normalization (16%) and the limited statistics of the Monte Carlo events (13%). As a cross check of the normalization, we also calculated this background using the VECBOS prediction for the $W^+ \geq 2j$ inclusive cross section and obtained a consistent result.

The backgrounds due to $t\bar{t} \rightarrow W^+W^-bb$, $WW \rightarrow \tau\nu jj$ and $ZX \rightarrow eeX$ were estimated using the ISAJET program followed by the GEANT detector simulation and found to be small. The total number of background events was estimated to be $75.5 \pm 13.3$. Thus we observed no statistically significant signal above the background.

The trigger and electron selection efficiencies [12] were estimated using $Z \rightarrow ee$ events. The jet finding efficiency is a function of $p_T^W$, due to the $E_T^j$ requirement in the low $p_T^W$ region and due to the probability for two jets to merge into one in the high $p_T^W$ region. Using the ISAJET and PYTHIA [13] event generators followed by a full detector simulation, we estimated the efficiency for $W \rightarrow jj$ selection, including the jet finding efficiency and the efficiency for the dijet mass requirement, as a function of $p_T^W$, shown in Fig. 3. In estimating the sensitivity to the anomalous $WW\gamma$ and $WWZ$ coupling parameters, we used the $W \rightarrow jj$ efficiency obtained from ISAJET, which is smaller than that from PYTHIA and therefore gives a conservative estimate. We included the difference between the ISAJET and PYTHIA numbers in the systematic uncertainty. We calculated the overall event selection
TABLE I. Summary of $evjj$ data and backgrounds.

| Background source:                                      | $evjj$ events |
|--------------------------------------------------------|---------------|
| $W^+ \geq 2j$                                          | 62.2 ± 13.0   |
| multijets                                              | 12.2 ± 2.6    |
| $\bar{t}t (m_t = 180 \text{ GeV}/c^2)$                | 0.87 ± 0.01   |
| $WW \rightarrow \tau \nu jj$                          | 0.19 ± 0.01   |
| $ZX \rightarrow eeX$                                  | 0.00$^{+0.34}_{-0.00}$ |
| Total Background                                       | 75.5 ± 13.3   |

| Data                                                   | 84            |
| SM $WW + WZ$ prediction                                | 2.9 ± 0.5     |

Efficiency as a function of the coupling parameters using the efficiencies described above and the $WW, WZ$ Monte Carlo program of Zeppenfeld [2,14], in which the processes were generated to leading order, and higher order QCD effects were approximated by a K-factor of $1 + \frac{2}{9}\pi \alpha_s = 1.34$. A dipole form factor with a scale $\Lambda = 1.5$ TeV was used in the Monte Carlo event generation (e.g. $\Delta \kappa_\gamma (\hat{s}) = \Delta \kappa / (1 + \hat{s} / \Lambda^2)^2$, where $\hat{s}$ is the square of the invariant mass of the $WW$ or $WZ$ system). We simulated the $p_T$ distribution of the $WW$ and $WZ$ systems using the observed $p_T^Z$ spectrum in our inclusive $Z \rightarrow ee$ data sample. We calculated the total efficiency with the SM couplings to be 0.15 ± 0.02 for $WW$ and 0.16 ± 0.02 for $WZ$. Thus the total number of expected SM events was 2.9 ± 0.5: 2.5 ± 0.5 for $WW$ and 0.4 ± 0.1 $WZ$. Using these efficiencies and the background-subtracted signal, we set the upper limit on the cross section times branching fraction of $\sigma B(W^+W^- \rightarrow e^\pm \nu jj) + \sigma B(W^\pm Z \rightarrow e^\pm \nu jj)$ for the SM couplings to be 17 pb at the 95% confidence level (CL). Figure 4 shows the $p_T$ distribution of the $e\nu$ system.

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, a binned likelihood fit was performed on the $p_T$ spectrum of the $e\nu$ system, by calculating the probability for the
sum of the background and the Monte Carlo signal prediction as a function of anomalous coupling parameters, to fluctuate to the observed number of events. The uncertainties in the background estimate, efficiencies, acceptance and integrated luminosity were convoluted in the likelihood function with Gaussian distributions. Figure 5 shows the limit contour at the 95\% CL for the CP–conserving anomalous coupling parameters, assuming that CP–violating anomalous coupling parameters are zero and that the $WW\gamma$ coupling parameters are equal to the $W\gamma\gamma$ coupling parameters: $\Delta\kappa \equiv \Delta\kappa_{\gamma} = \Delta\kappa_{Z}$ and $\lambda \equiv \lambda_{\gamma} = \lambda_{Z}$. We obtained limits at the 95\% CL of

$$-0.89 < \Delta\kappa < 1.07 \quad (\lambda = 0), \quad -0.66 < \lambda < 0.67 \quad (\Delta\kappa = 0),$$

for $\hat{s} = 0$ (i.e. the static limit). The limits obtained are within the constraints imposed by the S–matrix unitarity for $\Lambda = 1.5$ TeV. Figure 6 compares the limits obtained in this paper with limits obtained by DØ from a measurement of $W\gamma$ production [4] and a search for $WW \to \ell\ell'\nu\bar{\nu}'$ [5]. The preliminary result obtained from this analysis gives the most stringent limit on $\Delta\kappa$.

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* Visitor from IHEP, Beijing, China.
† Visitor from CONICET, Argentina.
‡ Visitor from Universidad de Buenos Aires, Argentina.
¶ Visitor from Univ. San Francisco de Quito, Ecuador.

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FIG. 1. Leading order Feynman diagrams for $q\bar{q} \to WW$ (a,b) and $q\bar{q}' \to WZ$ (c,d)
FIG. 2. $p_T$ distributions of Monte Carlo $WW \to e\nu jj$ events with various coupling parameters. The dotted line represents the Standard Model (SM) couplings. The cross section increases and the $p_T$ spectrum becomes harder with anomalous coupling parameters. The samples are normalized to $13.7 \text{ pb}^{-1}$. 

FIG. 3. Total efficiency for $W \rightarrow jj$ selection as a function of $p_T^W$, estimated using the ISAJET(solid) and the PYTHIA(dashed) generators followed by a full detector simulation.
FIG. 4. $p_T$ distributions of the $e\nu$ systems. The solid circle indicates the observed spectrum. The dashed and dotted lines are background estimates from the QCD multi-jet events and $W + \geq 2j$ events, and $W + \geq 2j$ events only respectively (top plot). The Monte Carlo predictions of $p_T$ spectrum of the $e\nu$ system for the SM and non-SM productions are shown in the bottom plot.
FIG. 5. Limit contour (solid line) on CP-conserving anomalous coupling parameters at the 95% CL, assuming $\Delta \kappa \equiv \Delta \kappa_\gamma = \Delta \kappa_Z$ and $\lambda \equiv \lambda_\gamma = \lambda_Z$. The constraint imposed by the S-matrix unitarity for $\Lambda = 1.5$ TeV is also shown (dotted line).
FIG. 6. Comparison of the limit obtained in this paper with limits obtained from a measurement of $W\gamma$ production [4] and a search for $WW \rightarrow \ell\ell'\nu\bar{\nu}$ [5].
solid: WW Δκ=2.0, λ=1.5

dashed: WW Δκ=2.0, λ=0.0

dotted: WW Δκ=0.0, λ=0.0 (SM)
Points: data
Dashed: QCD fakes and W$^+$ $\geq$ 2jets
Dotted: W$^+$ $\geq$ 2jets

Solid: QCD fakes and W$^+$ $\geq$ 2jets
Dotted: WW $\Delta \chi = 2$, $\lambda = 1.5$
Dashed: WW $\Delta \chi = 2$, $\lambda = 0$
Dot dashed: WW SM
from $WW \rightarrow l l \nu \bar{\nu}$

from $W \gamma$

from $WW, WZ \rightarrow e \nu jj$

(DØ Preliminary)