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Search for W Boson Pair Production in in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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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 dilepton ($e\mu, ee$, and $\mu\mu$) channels are presented. One event is observed with an expected background of 0.56 ± 0.13 events with an integrated luminosity of approximately 14 pb^{-1}. Assuming equal strengths for the WWZ and $WW\gamma$ gauge boson coupling parameters κ and λ, limits on the CP-conserving anomalous coupling constants are $-2.6 < \Delta\kappa < 2.8$ and $-2.2 < \lambda < 2.2$ at the 95% confidence level.

The Standard Model (SM) of electroweak interactions makes precise predictions for the gauge boson self-couplings due to the non-abelian gauge symmetry of $SU(2)_L \otimes U(1)_Y$. The $WW\gamma$ coupling has been studied using the cross section and photon transverse energy spectrum of $W\gamma$ events at UA2 [1], CDF [2], and DØ [3]. However, the WWZ trilinear coupling has not been previously tested. The W boson pair production process provides a direct test of both the $WW\gamma$ and WWZ couplings [4].

The leading-order SM diagrams for W boson pair production in $p\bar{p}$ collisions are u- and t-channel quark exchange as well as s-channel production with either a photon or a Z boson as the mediating particle. The latter process contains the $WW\gamma$ and WWZ trilinear couplings. The SM predicts that these couplings are $g_{WW\gamma} = -e$ and $g_{WWZ} = -e\cot\theta_W$ and that unitarity violation due to the u- and t-channel amplitudes (which depend on the well-known couplings between the W boson and quarks) is prevented by cancellations provided by the s-channel amplitudes. Thus, W boson pair production provides a test of the SM gauge structure.

A formalism has been developed to describe the $WW\gamma$ and WWZ interactions for models beyond the SM [5]. The general effective Lorentz invariant Lagrangian for the electroweak gauge couplings, after imposing C, P, and CP symmetry, contains six dimensionless coupling parameters: g_1^V, κ_V, and λ_V, where $V = \gamma$ or Z. g_1^Z is assumed to be equal to g_1^γ, which is restricted to unity by electromagnetic gauge invariance. The effective Lagrangian can be reduced to the SM Lagrangian by setting $\kappa_V = 1$ ($\Delta\kappa_V \equiv \kappa_V - 1 = 0$) and $\lambda_V = 0$. Throughout this letter, it is assumed that $\kappa_\gamma = \kappa_Z$ and $\lambda_\gamma = \lambda_Z$. The coupling parameters are related to the magnetic dipole moments (μ_W) and electric quadrupole moments (Q_W^e) of the W boson: $\mu_W = \frac{e}{2M_W}(1+\kappa+\lambda)$ and $Q_W^e = -\frac{e}{M_W^2}(\kappa-\lambda)$, where e and M_W are the charge and the mass of the W boson [6].

The effective Lagrangian leads to a W boson pair production cross section which grows with $\hat{s}$, the square of the invariant mass of the WW system, for non-SM values of the couplings. In order to avoid unitarity violation, the anomalous couplings are parameterized as form factors with a scale, Λ (*e.g.* $\Delta\kappa/(1+\hat{s}/\Lambda^2)^2$). By requiring that tree-level unitarity is satisfied, a constraint $\Lambda \leq \left(\frac{6.88}{(\kappa-1)^2+2\lambda^2}\right)^{1/4}$ TeV is obtained [4]. Limits on the coupling parameters κ and λ are obtained by comparing the measured cross section for W boson pair production to the predicted non-SM values; the cross section increases with κ and λ above the SM prediction of 9.5 pb [7].

In this letter the results of a search for $p\bar{p}(\sqrt{s} = 1.8$ TeV$) \rightarrow WW + X \rightarrow l\bar{l}'\bar{\nu}\nu' + X$, where the leptons include muons and electrons, are presented. The data sample corresponds to an integrated luminosity of approximately 14 pb^{-1} collected with the DØ detector during the 1992-93 Tevatron collider run at Fermilab.

The DØ detector [8] 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 energy resolution for electrons and photons is $15\%/\sqrt{E(\mathrm{GeV})}$. The resolution for the transverse component of missing energy, $\not\!\!E_T^{\mathrm{cal}}$, is $1.1\ \mathrm{GeV} + 0.02(\sum E_T)$, where $\sum E_T$ is the scalar sum of transverse energy, E_T, in GeV, deposited in the calorimeter. The central and forward drift chambers are used to identify charged tracks for $|\eta| \leq 3.2$. There is no central magnetic field. Muons are identified and their momentum measured with three layers of proportional drift tubes, one inside and two outside of the magnetized iron toroids, providing coverage for $|\eta| \leq 3.3$. The muon momentum resolution, determined from $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ events, is $\sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.008$ (p in GeV/c). The p_T of identified muons is used to correct $\not\!\!E_T^{\mathrm{cal}}$ to form the missing transverse energy, $\not\!\!E_T$.

Muons are required to be isolated, to have energy deposition in the calorimeter corresponding to at least that of a minimum ionizing particle, and to have $|\eta| \leq 1.7$. For the $\mu\mu$ channel, cosmic rays are rejected by requiring that the muons have timing consistent with the beam crossing. Electrons are identified through the longitudinal and transverse shape of isolated energy clusters in the calorimeter and by the detection of a matching track in the drift chambers. Electrons are required to be within a fiducial region of $|\eta| \leq 2.5$. A criterion on ionization (dE/dx), measured in the drift chambers, is imposed to reduce backgrounds from photon conversions and hadronic showers with large electromagnetic content.

The event samples come from triggers with dilepton signatures. The $e\mu$ sample is selected from events passing the trigger requirement of an electromagnetic cluster with $E_T \geq 7$ GeV and a muon with $p_T \geq 5$ GeV/c. The ee candidates are required to have two isolated electromagnetic clusters, each with $E_T \geq 10$ GeV. The $\mu\mu$ candidates are selected from events where at least one muon is identified with $p_T \geq 5$ GeV/c at the trigger level.

In the offline selection for the $e\mu$ channel, a muon with $p_T \geq 15$ GeV/c and an electron with $E_T \geq 20$ GeV are required. Both $\not\!\!E_T$ and $\not\!\!E_T^{\mathrm{cal}}$ are required to be ≥ 20 GeV. In order to suppress $Z \rightarrow \tau\bar{\tau}$ and $b\bar{b}$ backgrounds, it is required that $20^\circ \leq \Delta\phi(p_T^\mu, \not\!\!E_T) \leq 160^\circ$ if $\not\!\!E_T \leq 50$ GeV, where $\Delta\phi(p_T^\mu, \not\!\!E_T)$ is the angle in the transverse plane between the muon and $\not\!\!E_T$. One event survives these selection cuts in a data sample corresponding to an integrated luminosity of 13.5 ± 1.6 pb^{-1}.

For the ee channel, two electrons are required, each with $E_T \geq 20$ GeV. The $\not\!\!E_T$ is required to be ≥ 20 GeV. The Z

boson background is reduced by removing events where the dielectron invariant mass is between 77 and 105 GeV/c^2. It is required that $20^\circ \leq \Delta\phi(p_T^e, \not{E}_T) \leq 160^\circ$ for the lower energy electron if $\not{E}_T \leq 50$ GeV. This selection suppresses $Z \to ee$ as well as $\tau\tau$. The integrated luminosity in this channel is 13.9 ± 1.7 pb^{-1}. One event survives these selection requirements.

For the $\mu\mu$ channel, two muons are required, one with $p_T \geq 20$ GeV/c and another with $p_T \geq 15$ GeV/c. In order to remove Z boson events, it is required that the $\not{E}_T$ projected on the dimuon bisector in the transverse plane be greater than 30 GeV. This selection requirement is less sensitive to the momentum resolution of the muons than is a dimuon invariant mass cut. It is required that $\Delta\phi(p_T^\mu, \not{E}_T) \leq 170^\circ$ for the higher p_T muon. No events survive these selection requirements in a data sample corresponding to an integrated luminosity of 11.8 ± 1.4 pb^{-1}.

Finally, in order to suppress background from $t\bar{t}$ production, the vector sum of the E_T from hadrons, $\vec{E}_T^{\rm had}$, defined as $-(\vec{E}_T^{l1} + \vec{E}_T^{l2} + \vec{\not{E}}_T)$ is required to be less than 40 GeV in magnitude for all channels. Figure 1 shows a Monte Carlo simulation of $E_T^{\rm had}$ for ~ 20 fb^{-1} of SM WW and $t\bar{t}$ events. For WW events, non-zero values of $E_T^{\rm had}$ are due to gluon radiation and detector resolution. For $t\bar{t}$ events, the most significant contribution is the b-quark jets from the t-quark decays. This selection reduces the background from $t\bar{t}$ production by a factor of four for a t-quark mass of 160 GeV/c^2 and is slightly more effective for a more massive t-quark. The efficiency of this selection criterion for SM W boson pair production events is $0.95^{+0.01}_{-0.04}$ and decreases slightly with increasing W boson pair invariant mass. The surviving ee candidate passes this selection requirement but the $e\mu$ candidate [9] is rejected.

The detection efficiency for SM W boson pair production events is determined using the PYTHIA [10] event generator followed by a detailed GEANT [11] simulation of the DØ detector. Muon trigger and electron identification efficiencies are derived from the data. The overall detection efficiency for SM $WW \to e\mu$ is 0.092 ± 0.010. For the ee channel the efficiency is 0.094 ± 0.008. For the $\mu\mu$ channel it is 0.033 ± 0.003. For the three channels combined, the expected number of events for SM W boson pair production, based on a cross section of 9.5 pb [7], is 0.46 ± 0.08. The Monte Carlo program of Ref. [4] followed by a fast detector simulation [12] is used to estimate the detection efficiency for W boson pair production as a function of the coupling parameters λ and κ.

The backgrounds due to Z boson, Drell-Yan dilepton, $W\gamma$, and $t\bar{t}$ events are estimated using the PYTHIA and ISAJET [13] Monte Carlo event generators followed by the GEANT detector simulation. The backgrounds from $b\bar{b}$, $c\bar{c}$, multi-jet, and $W +$ jet events, where a jet is mis-identified as an electron, are estimated using the data. The $t\bar{t}$ cross section estimates are from calculations of Laenen *et al.* [14]. The $t\bar{t}$ background is averaged for $M_{\rm top} = 160$, 170, and 180 GeV/c^2. The background estimates are summarized in Table I.

Background	$e\mu$	ee	$\mu\mu$
$Z \to ee$ or $\mu\mu$	—	0.02 ± 0.01	0.066 ± 0.026
$Z \to \tau\tau$	0.11 ± 0.05	$< 10^{-3}$	$< 10^{-3}$
Drell-Yan dileptons	—	$< 10^{-3}$	$< 10^{-3}$
$W\gamma$	0.04 ± 0.03	0.02 ± 0.01	—
QCD	0.07 ± 0.07	0.15 ± 0.08	$< 10^{-3}$
$t\bar{t}$	0.04 ± 0.02	0.03 ± 0.01	0.009 ± 0.003
Total	0.26 ± 0.10	0.22 ± 0.08	0.075 ± 0.026

TABLE I. Summary of backgrounds to $WW \to ee$, $WW \to e\mu$ and $WW \to \mu\mu$. The units are expected number of background events in the data sample. The uncertainties include both statistical and systematic contributions.

The 95% confidence level upper limit on the W boson pair production cross section is estimated based on one signal event including a subtraction of the expected background of 0.56 ± 0.13 events. The branching ratio $W \to l\bar{\nu} = 0.108 \pm 0.004$ [15] is assumed. Poisson-distributed numbers of events are 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 91 pb at the 95% confidence level. From the observed limit, as a function of λ and κ, and the theoretical prediction of the W boson pair production cross section, the 95% confidence level limits on the coupling parameters shown in Fig. 2 (solid line) are obtained. Also shown in Fig. 2 (dotted line) is the contour of the unitarity constraint on the coupling limits for the form factor scale $\Lambda = 900$ GeV. This value of Λ is chosen so that the observed coupling limits lie within this ellipse. The limits on the CP-conserving anomalous coupling parameters are $-2.6 < \Delta\kappa < 2.8$ ($\lambda = 0$) and $-2.2 < \lambda < 2.2$ ($\Delta\kappa = 0$).

The coupling limits are insensitive to the decrease in the expected $t\bar{t}$ background which would occur if the top quark is much more massive than $160 - 180$ GeV/c^2. If the top background is negligible, the 95% confidence level upper limit for SM W boson pair production is 93 pb.

In conclusion, a search for $WW \to$ dileptons in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is made. In approximately 14 pb^{-1} of data, one event is found with an expected background of 0.56 ± 0.13 events. From the Standard Model, 0.46 ± 0.08 events are expected. For SM W boson pair production, the upper limit for the cross section is 91 pb at the 95% confidence level. The limits on the CP-conserving anomalous coupling parameters are $-2.6 < \Delta\kappa < 2.8$ ($\lambda = 0$) and $-2.2 < \lambda < 2.2$ ($\Delta\kappa = 0$) at the 95% confidence level where κ_γ and λ_γ are assumed to equal κ_Z and λ_Z, respectively. The limits on λ and $\Delta\kappa$ exhibit almost no correlation, in contrast to limits from Refs. [1-3]. The maximum form factor scale accessible for this experiment is $\Lambda = 900$ GeV.

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FIG. 1. $E_T^{\rm had}$ for Monte Carlo WW and $t\bar{t}$ events with $M_{\rm top} = 160$ GeV/c^2 ($\int Ldt \sim 20$ fb^{-1}). Events with $E_T^{\rm had} \geq 40$ GeV were rejected.

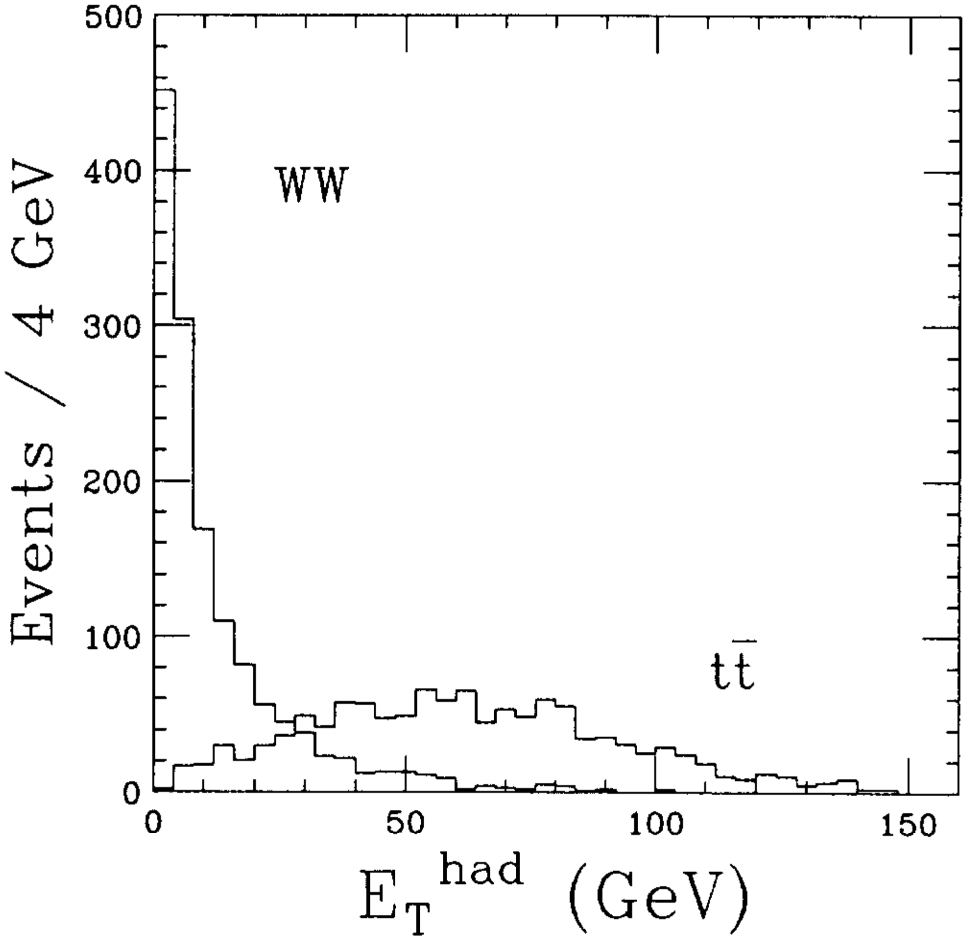

FIG. 2. 95% CL limits on the CP-conserving anomalous couplings λ and $\Delta\kappa$, assuming that $\lambda_\gamma = \lambda_Z$ and $\kappa_\gamma = \kappa_Z$. The dotted contour is the unitarity limit for the form factor scale $\Lambda = 900$ GeV which was used to set the coupling limits.