Measurement of the W^+W^- Production Cross Section and Search for Anomalous $WW\gamma$ and WWZ Couplings in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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This Letter describes the current most precise measurement of the W boson pair production cross section and most sensitive test of anomalous $WW\gamma$ and WWZ couplings in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. The WW candidates are reconstructed from decays containing two charged leptons and two neutrinos. Using data collected by the CDF II detector from 3.6 fb^{-1} of integrated luminosity, a total of 654 candidate events are observed with an expected background of 320 ± 47 events. The measured cross section is $\sigma(p\bar{p} \to W^+W^- + X) = 12.1 \pm 0.9(\text{stat})^{+1.6}_{-1.4}(\text{syst})$ pb, which is in good agreement with the standard model prediction. The same data sample is used to place constraints on anomalous $WW\gamma$ and WWZ couplings.

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The measurement of W boson pair production is an important test of the standard model (SM) of particle physics. This process is also an essential background to understand for Higgs boson searches. Next-to-leading order (NLO) calculations of W^+W^- production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV predict a cross section of $\sigma^{\rm NLO}(p\bar{p} \to W^+W^-) = 11.7 \pm 0.7$ pb [1,2]. The presence of anomalous $WW\gamma$ and WWZ triple-gauge boson couplings (TGCs) [3] could be indications of new physics at a higher mass scale, and would lead to rates for W^+W^- production or kinematic distributions that differ from those predicted by the SM.

This Letter reports a measurement of the W^+W^- production cross section and limits on anomalous TGCs using a final state consisting of two oppositely charged leptons and two neutrinos in $p\bar{p}$ collision data collected by the CDF II detector from 3.6 fb^{-1} of integrated luminosity. First evidence for W boson pair production was reported by CDF using Tevatron Run I data [4]. This process was later measured with greater significance by CDF and D0 using 184 pb^{-1} and 224–252 pb^{-1}, respectively, of integrated luminosity from Run II [5,6]. Recently, D0 measured the W^+W^- cross section with a precision of 20% using 1.0 fb^{-1} of integrated luminosity [7]. Limits on anomalous TGCs have previously been reported by LEP experiments as well as CDF and D0 [7,8].

The cross section measurement uses a matrix element method in which the probability for each event to have been produced by each of several relevant SM processes is calculated. A likelihood ratio (LR) is formed from these probabilities. The predicted shapes and normalizations of the signal and background LR distributions are used to extract the SM W^+W^- production cross section via a maximum-likelihood fit to the LR distribution observed in data. In general, the presence of anomalous TGCs will increase the number of events containing leptons with very high values of momentum. Transverse momentum, p_T, is the track momentum component transverse to the beam line. Limits on anomalous TGCs are determined from the shape and normalization of the p_T spectrum constructed from the lepton in the event with the highest p_T, referred to as the leading lepton. The results are reported in the HISZ scheme, where three parameters, λ_Z, g_1^Z, and κ_γ, are used to describe all dimension-six operators which are Lorentz and $SU(2)_L \otimes U(1)_Y$ invariant and conserve C and P separately [9]. In the SM, $\lambda_Z = 0$ and $g_1^Z = \kappa_\gamma = 1$. In this Letter, Δg_1^Z and $\Delta\kappa_\gamma$ are used to denote the deviation of the g_1^Z and κ_γ parameters from their SM values. The non-SM values of the parameters λ_Z, g_1^Z, and κ_γ are functions of the invariant mass of the W^+W^- system, $\sqrt{\hat{s}}$. These results probe a larger range of values of $\sqrt{\hat{s}}$ and thus may only be qualitatively compared to the results from LEP, which were below $\sqrt{\hat{s}} = 209$ GeV. For hadron collisions, a dipole form factor for an arbitrary coupling $\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$ [9] is introduced to turn off the coupling at large $\sqrt{\hat{s}}$ and avoid a violation of unitarity. The form factor scale Λ is the scale of new physics.

In the CDF II detector [10], a particle's direction is characterized by the azimuthal angle ϕ and the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle measured from the proton beam direction. The transverse energy E_T is defined as $E\sin\theta$, where E is the energy in the calorimeter towers associated with a cluster of energy deposition. The magnitude of the p_T for an electron is scaled according to the energy measured in the calorimeter. The missing transverse energy vector, $\vec{\not\!\!E}_T$, is defined as $-\sum_i E_T^i \hat{n}_T^i$, where $\hat{n}_T^i$ is the unit vector in the transverse plane pointing from the interaction point to the energy deposition in calorimeter tower i. This is corrected for the p_T of muons, which do not deposit all of their energy in the calorimeter. The scalar $\not\!\!E_T$ is defined as $|\vec{\not\!\!E}_T|$. Strongly interacting partons produced in the $p\bar{p}$ collision undergo fragmentation that results in highly collimated jets of hadronic particles. Jet candidates are reconstructed using the calorimeter and are required to have $E_T > 15$ GeV and $|\eta| < 2.5$. Isolated lepton candidates are accepted out to an $|\eta|$ of 2.0 for electron candidates and $|\eta|$ of 1.0 for muon candidates.

The experimental signature for the decay $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ is two leptons with opposite charge and $\not\!\!E_T$ from the neutrinos which escape undetected. In this Letter, ℓ refers to an electron or muon. Additional signal acceptance ($\sim$12%) is obtained from cases where one or both W bosons decay to a τ lepton which subsequently decays to an electron or muon. There are several SM processes which result in a similar final state to W^+W^- and are therefore backgrounds in this measurement. These are other diboson production (WZ, ZZ) and top-quark pair production ($t\bar{t}$). It is also possible to observe apparent $\not\!\!E_T$ arising from the mismeasurement of lepton energy, lepton momentum, or the hadronic part of the final state. Drell-Yan ($Z/\gamma^* \to \ell^+\ell^-$) events have no neutrinos in the final state, but due to large production rates enter the W^+W^- candidate sample via mismeasurements. A third source of background is events in which a final-state particle is misidentified. These are W + jets and $W\gamma$ production, where the W boson decays leptonically and a jet is reconstructed as a lepton candidate or the γ converts in the detector material and is reconstructed as an electron.

Events containing two oppositely charged lepton candidates are selected from the data sample. The online event triggering and selection of lepton candidates are identical to those used in the search for SM Higgs bosons decaying to two W bosons at CDF [11]. The leading-lepton p_T is required to be above 20 GeV$/c$ to satisfy the trigger requirements, while the second lepton is allowed to have p_T as low as 10 GeV$/c$. The requirement is also made that events contain no jet candidates, which significantly reduces the $t\bar{t}$ background. A variant of $\not\!\!E_T$ used in selecting candidate events is defined as $\not\!\!E_{T,\mathrm{rel}} = \not\!\!E_T \sin\Delta\phi(\not\!\!E_T, \ell)$ when $\Delta\phi(\not\!\!E_T, \ell) \leq \frac{\pi}{2}$, where $\Delta\phi(\not\!\!E_T, \ell)$ is the azimuthal separation between the $\vec{\not\!\!E}_T$ and the momentum vector of the nearest lepton candidate. If $\Delta\phi(\not\!\!E_T, \ell) > \frac{\pi}{2}$, then $\not\!\!E_{T,\mathrm{rel}} = \not\!\!E_T$. The $\not\!\!E_{T,\mathrm{rel}}$ variable is designed to reject events where the apparent $\not\!\!E_T$ arises from the mismeasurement of lepton energy or momentum, and is required to be above 25 GeV to reduce the otherwise large Drell-Yan contamination. This requirement is lowered to 15 GeV for electron-muon events. The $W\gamma$ and heavy-flavor (J/ψ, Υ) backgrounds are reduced by requiring that the invariant mass of the lepton pair be greater than 16 GeV$/c^2$. The overall selection efficiency for W^+W^- events is about 7.5%.

With the exception of the W + 1-jet background, the acceptance and kinematic properties of the signal and background processes are determined by simulation. Events from W^+W^- are simulated at NLO using the MC@NLO generator [2]. The $t\bar{t}$, WZ, ZZ, and Drell-Yan backgrounds are simulated with the PYTHIA generator [12]. The $W\gamma$ background is determined using the generator described in Ref. [13]. The response of the CDF II detector is modeled with a GEANT-3-based simulation [14]. The expected yields for each process are normalized to the cross sections calculated at partial next-to next-to-leading order ($t\bar{t}$ [15]), NLO (W^+W^- [1,2], WZ and ZZ [1]), or leading-order with estimated higher-order corrections ($W\gamma$ [13] and Drell-Yan [16]). Efficiency corrections for the simulated detector response to lepton candidates are determined using samples of observed $Z \rightarrow \ell^+\ell^-$ events. The W + 1-jet background is calculated using the probability, measured in independent jet-triggered data samples, that a hadronic jet will be reconstructed as a lepton candidate. These probabilities are applied to the jet in the W + 1-jet data sample to estimate the number of such events which will pass the full lepton identification and signal selection criteria. The expected signal and background contributions are given in Table I along with the observed number of events.

The dominant systematic uncertainties on the estimated contributions come from the luminosity measurement (6%) [17] and the simulated acceptances of the signal and background processes. The acceptance uncertainty due to the parton distribution function modeling ranges from 1.9% to 4.1% for the different processes. A 10% uncertainty is assigned to all simulated processes for the kinematic differences between leading-order and higher-order calculations, based on the difference in acceptance of W^+W^- events simulated at leading order and NLO using the PYTHIA and MC@NLO generators, respectively. The cross section uncertainties are 6% on diboson production, 10% on $t\bar{t}$ and $W\gamma$ production, and 5% on Drell-Yan production. A 21% uncertainty is included for the Drell-Yan background to account for the mismodeling of $\not\!\!E_T$ and jet production rates. Systematic uncertainties of 20% and 27% are assigned to the $W\gamma$ and W + 1-jet background estimates, respectively, due to uncertainties in the modeling of the photon conversions and misidentification of a jet as a lepton. Uncertainties on the modeling of jets accounts for 2% to 4% and lepton identification and trigger efficiencies range from 1% to 7%.

TABLE I. Expected number of signal (W^+W^-) and background events along with the total number of expected and observed events in the data. Uncertainties include all systematic uncertainties described in the text.

Process	Events
Z/γ^* (Drell-Yan)	79.8 ± 18.4
WZ	13.8 ± 1.9
$W\gamma$	91.7 ± 24.8
W + 1-jet	112.7 ± 31.2
ZZ	20.7 ± 2.8
$t\bar{t}$	1.3 ± 0.2
Total background	320.0 ± 46.8
W^+W^-	317.6 ± 43.8
Total expected	637.6 ± 73.0
Data	654

For each event passing the signal selection criteria, four matrix-element-based event probabilities are calculated corresponding to the production and decay processes $W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$, $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, W + 1-jet $\rightarrow \ell\nu+$ 1-jet, and $W\gamma \rightarrow \ell\nu + \gamma$. In the latter two processes, the jet or γ is assumed to have been reconstructed as a charged lepton candidate. The event probability for a process X is given by

$$P_X(\vec{x}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}, \vec{y}) d\vec{y} \quad (1)$$

where $\vec{x}$ represents the observed lepton momenta and $\vec{\not\!\!E}_T$ vectors, $G(\vec{x}, \vec{y})$ is a transfer function representing the detector resolution, and $\epsilon(\vec{y})$ is an efficiency function parametrized by η which quantifies the probability for a particle to be reconstructed as a lepton. The differential cross section $\frac{d\sigma(\vec{y})}{d\vec{y}}$ is calculated using leading-order matrix elements from the MCFM program [1] and integrated over all possible true values of the final-state particle four-vectors $\vec{y}$. The normalization factor $\langle\sigma\rangle$ is determined from the leading-order cross section and detector acceptance for each process. These event probabilities are combined into a likelihood ratio $\mathrm{LR}_{WW} = \frac{P_{WW}}{P_{WW}+\sum_j k_j P_j}$, where $j = \{ZZ, W + 1\text{-jet}, W\gamma\}$ and k_j is the relative fraction of the expected number of events for the jth process such that $\sum_j k_j = 1$. The templates of the LR_{WW} distribution are created for signal and each background process.

A binned maximum likelihood is used to extract the W^+W^- production cross section from the shape and normalization of the LR_{WW} templates. The likelihood is formed from the Poisson probabilities of observing n_i events in the ith bin when μ_i are expected. Variations corresponding to the systematic uncertainties are included as normalization parameters for signal and background, constrained by Gaussian terms. The likelihood is given by

$$\mathcal{L} = \left(\prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}\right)\prod_c e^{-(S_c^2/2)}, \qquad (2)$$

where $\mu_i = \sum_k \alpha_k [\prod_c (1 + f_k^c S_c)](N_k^{\mathrm{exp}})_i$, f_k^c is the fractional uncertainty for the process k due to the systematic c, and S_c is a floating parameter associated with the systematic uncertainty c. The correlations of systematic uncertainties between processes are accounted for in the definition of μ_i. The expected number of events from process k in the ith bin is given by $(N_k^{\mathrm{exp}})_i$. The parameter α_k is an overall normalization parameter for process k and is fixed to unity for all processes other than W^+W^-, for which it is freely floating. The likelihood is maximized with respect to the systematic parameters S_c and α_{WW} using the MINUIT program [18]. This method gives a measured value for the W^+W^- production cross section of $\sigma(p\bar{p} \to W^+W^- + X) = 12.1 \pm 0.9(\mathrm{stat})^{+1.6}_{-1.4}(\mathrm{syst})$ pb. The fit to the data of the signal and sum of the individually fitted background templates is shown in Fig. 1.

The likelihood of the observed leading-lepton p_T distribution is used to set limits on anomalous TGC values. The robustness of the leading-lepton p_T distribution has been verified using the same lepton selection in several non-overlapping final state kinematic regions. The response of the detector to events with different coupling constants is simulated for six points in the parameter space near the existing limits [8]. The efficiency multiplied by acceptance as a function of the leading-lepton p_T is taken to be the average of the values measured in these samples. The uncertainty is taken to be the maximum variation among these samples and ranges from 7% at low p_T to 50% at high p_T. This p_T-dependent efficiency is applied to the NLO generator-level distributions produced by the MCFM program [1] to predict the leading-lepton p_T spectrum for the coupling values considered, as shown in Fig. 2.

Each of the likelihoods $\mathcal{L}(\lambda_Z)$, $\mathcal{L}(\Delta g_1^Z)$, and $\mathcal{L}(\Delta\kappa_\gamma)$ are computed as the product over all bins in the leading-lepton p_T distribution of the Poisson probability of each bin given the model, and 95% confidence levels are set where $(-2\ln\mathcal{L}) - (-2\ln\mathcal{L}_{\mathrm{min}}) = (1.96)^2$. The systematic uncertainties include all those described for the W^+W^- cross section and the additional p_T-dependent uncertainty on the efficiency described previously. Systematic uncertainties are implemented by simultaneously applying all variations which reduce the sensitivity. The observed 95% confidence limits, shown in Table II, are weaker than expected. The probability of observing these limits in the presence of only standard model W^+W^- production ranges from 7.1% to 7.6% depending on the coupling constants (λ_Z, g_1^Z, κ_γ) and is deemed to be consistent with a statistical fluctuation.

In summary, the W^+W^- production cross section has been measured in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV from reconstructed events in the dilepton final state using a likelihood ratio formed from matrix-element-based event probabilities. This result is the most precise measurement at this energy with an overall uncertainty of less than 15%. The same event sample is also used to perform the most sensitive probe to date at this energy of anomalous WWZ and $WW\gamma$ couplings. The leading-lepton p_T distribution of the sample is found to be in moderate agreement with the

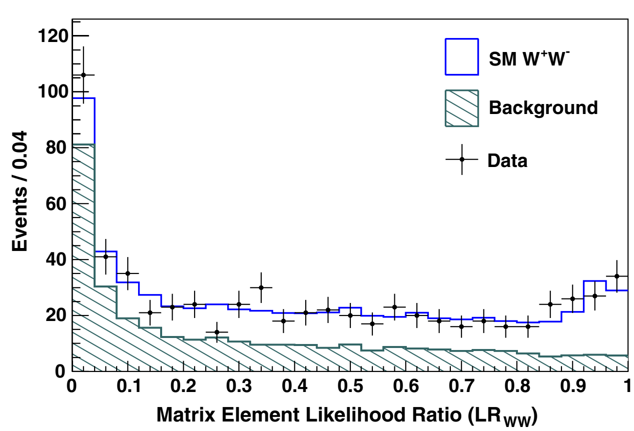

FIG. 1 (color online). The LR_{WW} distributions for the signal (W^+W^-) and background processes after a maximum-likelihood fit to the data.

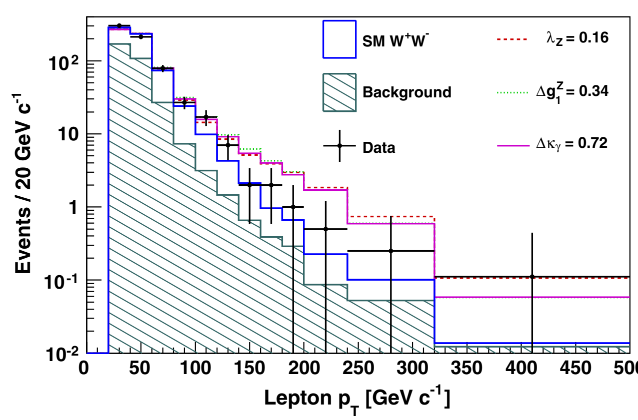

FIG. 2 (color online). Leading-lepton p_T distribution for data compared to the SM expectation. Also shown is how the expectation would be modified by anomalous couplings near the observed limits.

TABLE II. Expected and observed limits on anomalous TGCs. For each coupling limit set, the two other couplings are fixed at their SM values. Values of the couplings outside of the given observed range are excluded at the 95% confidence level.

	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Expected	1.5	(−0.05, 0.07)	(−0.09, 0.17)	(−0.23, 0.31)
Observed	1.5	(−0.16, 0.16)	(−0.24, 0.34)	(−0.63, 0.72)
Expected	2.0	(−0.05, 0.06)	(−0.08, 0.15)	(−0.20, 0.27)
Observed	2.0	(−0.14, 0.15)	(−0.22, 0.30)	(−0.57, 0.65)

SM expectation and used to place limits on anomalous triple-gauge couplings.

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[1] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
[2] S. Frixione and B. R. Webber, J. High Energy Phys. 06 (2002) 029.
[3] J. Ellison and J. Wudka, Annu. Rev. Nucl. Part. Sci. **48**, 33 (1998).
[4] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **78**, 4536 (1997).
[5] D. E. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 211801 (2005).
[6] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **94**, 151801 (2005); **100**, 139901(E) (2008).
[7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **103**, 191801 (2009).
[8] J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **54**, 345 (2008); S. Schael *et al.* (ALEPH Collaboration), Phys. Lett. B **614**, 7 (2005); P. Achard *et al.* (L3

Collaboration), Phys. Lett. B **586**, 151 (2004); G. Abbiendi *et al.* (OPAL Collaboration), Eur. Phys. J. C **33**, 463 (2004); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **74**, 057101 (2006); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **76**, 111103 (2007).

[9] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993).

[10] A. Abulencia *et al.* (CDF Collaboration), J. Phys. G **34**, 2457 (2007).

[11] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **102**, 021802 (2009).

[12] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.

[13] U. Baur, T. Han, and J. Ohnemus, Phys. Rev. D **57**, 2823 (1998).

[14] R. Brun, R. Hagelberg, M. Hansroul, and J. C. Lassalle, version 3.15, Report No. CERN-DD-78-2-REV.

[15] S. Moch and P. Uwer, Nucl. Phys. B, Proc. Suppl. **183**, 75 (2008).

[16] C. Anastasiou, L. J. Dixon, K. Melnikov, and F. Petriello, Phys. Rev. D **69**, 094008 (2004).

[17] D. Acosta *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **494**, 57 (2002).

[18] F. James and M. Roos, Comput. Phys. Commun. **10**, 343 (1975).