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CDF**

Observation of $W^+ W^-$ Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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Observation of W^+W^- Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present results of a search for W^+W^- production through the leptonic decay channel $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. In a 108 pb⁻¹ data sample recorded with the Collider Detector at Fermilab, five W^+W^- candidates are found with an expected Standard Model background of 1.2 ± 0.3 events. The W^+W^- production cross section is measured to be $\sigma(\bar{p}p \rightarrow W^+W^-) = 10.2^{+6.3}_{-5.1}$ (stat) ± 1.6 (syst) pb, in agreement with the Standard Model prediction. Limits on $WW\gamma$ and WWZ anomalous couplings are presented.

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Observation of W^+W^- production in $\bar{p}p$ collisions provides an opportunity to test the Standard Model prediction of $WW\gamma$ and WWZ couplings [1]. The gauge structure of the $SU(2) \times SU(1)$ theory of electroweak interactions governs trilinear vector boson couplings, and leads to a cancellation of helicity amplitudes. Anomalous couplings [2], or decays of new particles such as Higgs bosons, heavy quarks and leptons, and technihadrons, result in enhanced W^+W^- production [3, 4].

In this Letter we describe a search for W^+W^- production through the dilepton channel $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ ($l = e, \mu$), and compare the results with the Standard Model prediction. This analysis is based on a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 108 pb^{-1} , collected at the Collider Detector at Fermilab (CDF) from 1992 to 1995. Based on our observation of several $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ candidates, we measure $\sigma(\bar{p}p \rightarrow W^+W^-)$. Bounds on $WW\gamma$ and WWZ anomalous couplings are also obtained.

The CDF is described in detail in Ref. [5, 6]. The detailed description of the lepton identification cuts can be found in Ref. [6]. A lepton is identified by either hits in a muon chamber or a cluster of energy in the electromagnetic calorimeter, and an associated track in the central tracking chamber (CTC). The jet reconstruction algorithm uses a cone of fixed radius (0.4 in this analysis) in the η - ϕ plane to locate clusters of calorimeter energy. Here $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity, θ is the polar angle with respect to the proton beam direction, and ϕ is the azimuthal angle. The missing transverse energy $\cancel{E}_T$ associated with neutrinos is calculated by requiring that the total transverse energy as measured by the calorimeter be balanced. When a muon is present in the event the $\cancel{E}_T$ is corrected for the muon transverse momentum. In this analysis, electrons are required to have transverse energy $E_T > 20$ GeV, and muons transverse momentum $P_T > 20$ GeV/c.

The total $W^+W^- \rightarrow l^+l^- + X$ detection efficiency can be decomposed into several factors:

$$\epsilon_{total} = \epsilon_{geom.P_T} \times \epsilon_{ID} \times \epsilon_{Isol} \times \epsilon_{event} \times \epsilon_{0-jet} \times \epsilon_{trigger}.$$

The efficiency factors, described below, are computed sequentially and are listed in Table I. In addition to $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ ($l = e, \mu$), there is a small contribution from $W^+W^- \rightarrow l\tau\nu\bar{\nu}$ or $\tau\tau\nu\bar{\nu}$, followed by $\tau \rightarrow e$ or μ , which is included in our acceptance.

The acceptance due to geometrical and transverse momentum cuts, denoted by $\epsilon_{geom.P_T}$, is the fraction of $W^+W^- \rightarrow l^+l^- + X$ events for which both leptons are inside the detector fiducial region and pass the P_T cut. This efficiency is obtained from W^+W^- Monte Carlo samples. Several Monte Carlo event generators (ISAJET [7], TAOHAN [8], and PYTHIA [9]) are used in conjunction with a detector simulation. While ISAJET and PYTHIA use tree-level matrix element calculations to simulate the

TABLE I. Dilepton detection efficiencies.

Category	$e-e$	$\mu-\mu$	$e-\mu$
$\epsilon_{geom.P_T}$ (%)	30.0	20.0	28.8
ϵ_{ID} (%)	66.1	86.1	73.6
ϵ_{Isol} (%)	94.5	88.7	90.1
ϵ_{event} (%)	54.8	56.3	73.1
ϵ_{0-jet} (%)	68.0	68.0	68.0
$\epsilon_{trigger}$ (%)	98.1	92.8	93.5
ϵ_{total} (%)	6.9 ± 0.8	5.4 ± 0.7	8.9 ± 1.1

$W^+W^- + \text{jets}$ process, TAOHAN is based on the full matrix element calculation up to $W^+W^- + 2\text{jets}$.

The efficiency of the lepton identification cuts, ϵ_{ID} , is determined from $Z \rightarrow e^+e^-$ ($\mu^+\mu^-$) data samples.

All leptons are required to pass a calorimeter isolation cut—the total transverse energy in a cone with a radius 0.4 around the lepton in the η - ϕ plane, excluding the lepton transverse energy, divided by the lepton transverse energy must be less than 0.1. A track isolation cut is also applied to both leptons—the sum of the transverse momenta for all tracks in the above cone, excluding the lepton track, divided by the P_T of the lepton must be less than 0.1. The efficiency of these two cuts is denoted by ϵ_{Isol} .

To discriminate against backgrounds from $Z \rightarrow \tau\tau$ and the Drell-Yan process ($\gamma/Z \rightarrow e^+e^-, \mu^+\mu^-$), events are required to have a minimum $\cancel{E}_T$ of 25 GeV. We also reject events where $\cancel{E}_T$ points along the ϕ direction of one of the leptons [6]. For events with $\cancel{E}_T < 50$ GeV, we require $\Delta\phi > 20^\circ$, where $\Delta\phi$ is the azimuthal angle between the direction of $\cancel{E}_T$ and the direction of the nearest lepton. Also we remove events with dilepton invariant mass between 75 and 105 GeV/ c^2 in the e^+e^- and $\mu^+\mu^-$ channels. The combined efficiency of the $\cancel{E}_T$ and invariant mass cuts is denoted by ϵ_{event} .

The top quark production background ($\bar{p}p \rightarrow t\bar{t} + X \rightarrow W^+W^-b\bar{b} + X$) is suppressed by removing events with any jet with observed transverse energy exceeding 10 GeV (0-jet requirement). The fraction of $W^+W^- \rightarrow l^+l^- + X$ events with no jets is denoted by ϵ_{0-jet} . Simulations of $W^+W^- \rightarrow l^+l^- + X$ production indicate $\epsilon_{0-jet} = (68 \pm 7)\%$. Uncertainties are set by the difference between the Monte Carlo programs.

Single lepton (e or μ) hardware triggers were used to collect the data for this analysis. Their efficiencies were measured using data coming from independent triggers. The overall trigger efficiency, $\epsilon_{trigger}$, is the probability that a signal event is collected by any of the single lepton triggers.

Systematic uncertainties in the efficiency calculations come from the lepton identification cuts (3%), lepton isolation cuts (2%), event cuts (4%), choice of parton distribution functions (3%), 0-jet requirement (10%), and Monte Carlo statistics (3%). A 10% uncertainty on the

TABLE II. Predicted background events in the 108 pb⁻¹ data sample.

Process	Without 0-jet cut	All cuts
$t\bar{t}$	5.00 ± 1.00	0.04 ± 0.01
$Z \rightarrow \tau\tau$	0.59 ± 0.18	0.22 ± 0.06
Drell-Yan	1.90 ± 0.57	0.40 ± 0.20
WZ	0.17 ± 0.06	0.12 ± 0.05
Fake	1.80 ± 0.72	0.40 ± 0.20
Total	9.58 ± 1.37	1.18 ± 0.29

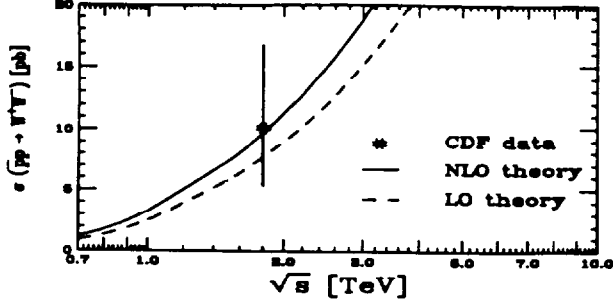


FIG. 1. The W^+W^- production cross section, $\sigma(\bar{p}p \rightarrow W^+W^-)$, measured at the CDF, compared to theoretical calculations. The theoretical results are based on the next-to-leading order (NLO) (solid line) and leading order (LO) (dashed line) calculations.

jet energy scale affects the jet multiplicity and the accuracy of the E_T measurement, and results in a 4% uncertainty in acceptance. The total uncertainty in the efficiency determination (13%) is the sum of these uncertainties in quadrature.

Table II summarises the expected background from $t\bar{t} \rightarrow W^+W^-b\bar{b}$, $Z \rightarrow \tau\tau$, the Drell-Yan process, WZ production, and W + jets processes in which jets are misidentified as leptons (fakes). Backgrounds are also listed when the 0-jet requirement is removed. Other backgrounds, such as $b\bar{b}$, ZZ and $Z \rightarrow b\bar{b}$, are found to be negligible.

The number of $W^+W^- \rightarrow l^+l^- + X$ events can be written as

$$N_{events} = \sigma(\bar{p}p \rightarrow W^+W^-) \cdot B \cdot \epsilon_{total} \cdot \int \mathcal{L} dt,$$

where $\int \mathcal{L} dt = 108 \pm 10$ pb⁻¹ is the integrated luminosity. A first order- α_s calculation [10] finds the continuum W^+W^- production cross section $\sigma(\bar{p}p \rightarrow W^+W^-)$ to be 9.5 pb with 30% theoretical uncertainty. Using 0.011 as the branching ratio, B , for $W^+W^- \rightarrow ee\nu\bar{\nu}$ and $\mu\mu\nu\bar{\nu}$, and 0.022 for $W^+W^- \rightarrow e\mu\nu\bar{\nu}$, we expect a signal of 3.5 ± 1.2 events.

Five events (two ee and three $e\mu$) survive the selection cuts in our data sample. Given $N_{events} = 3.8$ after background subtraction, from the above equation we obtain

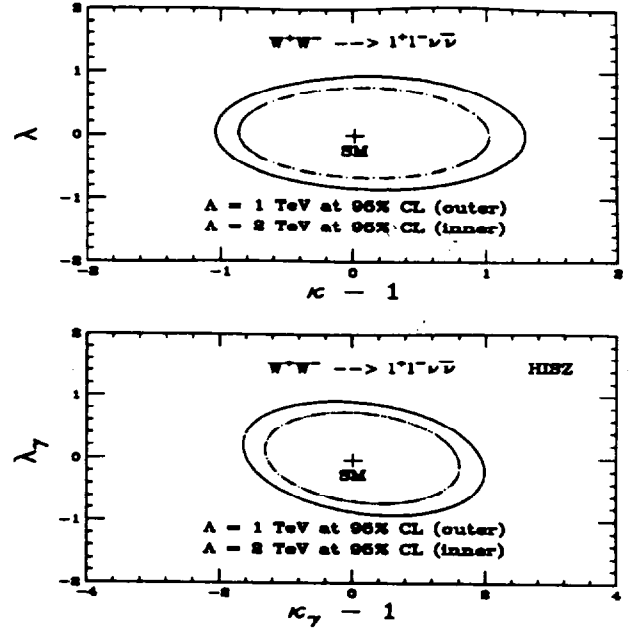


FIG. 2. Limits on anomalous couplings: (a) Assuming $\kappa_\gamma = \kappa_Z = \kappa$ and $\lambda_\gamma = \lambda_Z = \lambda$. (b) The HISZ scenario where κ_γ and λ_γ are used as independent parameters. The Standard Model value is located at the center. The outer (inner) contour is the 95 % CL limits with the energy scale $\Lambda = 1$ TeV (2 TeV).

$$\sigma(\bar{p}p \rightarrow W^+W^-) = 10.2_{-5.1}^{+6.3} (\text{stat}) \pm 1.6 (\text{syst}) \text{ pb}.$$

In Figure 1, the measured cross section is compared to leading order (LO) [1] and next-to-leading order (NLO) [10, 11] calculations. The CDF measurement of $\sigma(\bar{p}p \rightarrow W^+W^-)$ is consistent with the Standard Model prediction.

For WWV anomalous couplings ($V = \gamma, Z$), the most general effective Lagrangian, which is Lorentz, C, and P invariant, may be described in terms of six couplings denoted by g_1^V , κ_V , and λ_V . In the Standard Model, $g_1^V = 1$, $\kappa_V = 1$, and $\lambda_V = 0$ [2]. To ensure the unitarity of the theory, a dipole form factor of the form $1/(1 + \hat{s}/\Lambda^2)^2$ is introduced, where $\hat{s}$ is the subprocess mass squared and Λ is the energy scale beyond which new resonance particles, multiple boson production, and other new phenomena are expected.

To study WWV anomalous couplings, a tree-level Monte Carlo generator [2] is used to generate $W^+W^- \rightarrow l^+l^- + X$ events and the output is fed to the detector simulation. Since there are no QCD corrections in this generator and we are only interested in the relative deviation from the Standard Model prediction, the number of $W^+W^- \rightarrow l^+l^- + X$ events with couplings at their Standard Model values is normalised to that from the ISAJET calculation. The effect of QCD corrections on anomalous couplings is expected to be small at the Tevatron energy [12, 13].

Limits on anomalous couplings are obtained in one scenario that assumes $\kappa_\gamma = \kappa_Z = \kappa$ and $\lambda_\gamma = \lambda_Z = \lambda$. In the "HISZ" scenario [14], on the other hand, λ_γ and κ_γ are chosen as independent parameters. Contour limits at the 95% confidence level (CL) are shown in Figure 2, with the choices $\Lambda = 1, 2$ TeV. For a comprehensive review on anomalous couplings, see Ref. [15, 16].

In conclusion, we observe five dilepton events consistent with W^+W^- production with an expected background of 1.2 ± 0.3 . The probability that the observed events correspond to a fluctuation of the background is 1.1%. The W^+W^- production cross section is measured to be $\sigma(\bar{p}p \rightarrow W^+W^-) = 10.2^{+6.3}_{-5.1}$ (stat) ± 1.6 (syst) pb. This cross section is consistent with the NLO Standard Model prediction and limits are placed on $WW\gamma$ and WWZ anomalous couplings.

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