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Search for ZZ and ZW production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for ZZ and ZW vector boson pair production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the leptonic decay channels $ZZ \to ll\nu\nu$, $ZZ \to ll l' l'$, and $ZW \to ll l' \nu$. In a data sample corresponding to an integrated luminosity of 194 pb^{-1} collected with the Collider Detector at Fermilab, 3 candidate events are found with an expected background of 1.0 ± 0.2 events. We set a 95% confidence level upper limit of 15.2 pb on the cross section for ZZ plus ZW production, compared to the standard model prediction of 5.0 ± 0.4 pb.

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The measurements of ZZ and ZW production provide a direct test of the standard model (SM) prediction of triple-gauge-boson couplings [1]. The presence of unexpected neutral triple-gauge-boson couplings (ZZZ and $ZZ\gamma$) can result in an enhanced rate of ZZ production, and an anomalous WWZ coupling can increase the ZW production rate above the SM prediction. The WWZ and $ZZ\gamma$ couplings have been studied by the CDF and D0 experiments through the study of WW, ZW, $W\gamma$, and $Z\gamma$ production [2–8]. The D0 experiment has measured an upper limit on the cross section for ZW production [4]. No limit has been set on the cross section for ZZ production from hadron collisions, but production properties have been studied at LEP II in e^+e^- collisions at $\sqrt{s} = 183 - 209$ GeV [9]. A comprehensive review of the limits on anomalous WWZ, ZZZ, and $ZZ\gamma$ couplings at LEP II can be found in Ref. [10]. The production of WZ and ZZ boson pairs is also of interest because the decays cause significant backgrounds in searches for the SM Higgs boson.

In this report we present a search for ZZ and ZW production using the three decay modes $ZZ \to ll\nu\nu$, $ZZ \to ll l' l'$, and $ZW \to ll l' \nu$, where l and l' are electrons or muons, predominantly from direct W or Z decays, but also with a small contribution from the leptonic decay of tau leptons. This study is based on (194 ± 12) pb^{-1} [11] of data collected by the upgraded Collider Detector at

Fermilab (CDF II) from March 2002 to September 2003 using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. CDF II is a general-purpose detector at the Tevatron accelerator at Fermilab. The main components used in this analysis are a silicon vertex detector, a central tracking drift chamber, central ($|\eta| < 1.1$ [12]) and forward ($1.1 < |\eta| < 3.6$) electromagnetic and hadronic calorimeters, and muon chambers. The silicon detector and central tracking chamber are located inside a 1.4 T superconducting solenoidal magnet. A more detailed description of the detector can be found in the CDF technical design report [13] and in a recent publication describing a measurement of WW pair production [8].

The data samples are collected by a trigger system that selects events having electron candidates in the central calorimeter with $E_T > 18$ GeV, or muon candidates with $p_T > 18$ GeV$/c$. Events for this analysis are then selected by requiring at least two leptons with $E_T > 20$ GeV and $|\eta| < 2.5$ for electrons, or $p_T > 20$ GeV$/c$ and $|\eta| < 1$ for muons. An electron is identified as energy deposited in the central electromagnetic calorimeter which is matched to a well-measured track reconstructed in the central tracking chamber, or, for an electron with $|\eta| > 1.2$, as energy deposited in the forward electromagnetic calorimeter with an associated track utilizing a calorimeter-seeded silicon tracking algorithm [14]. In addition, electrons must have appropriate shower profiles in the electromagnetic calorimeters. A muon is identified as a track in the central tracking chamber, with energy deposition in the calorimeter consistent with a minimum ionizing particle, and with a track segment in the muon chambers. If a minimum ionizing track points towards a gap in the muon chamber coverage, it is still considered a muon candidate in events that have an additional electron in the central calorimeter or a muon with a muon chamber track segment. All charged leptons are required to be isolated from additional nearby calorimeter activity. The transverse energy deposited around an electron or muon in a cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$, excluding the calorimeter energy matched to the lepton candidate, is required to be less then 10% of the electron E_T or muon p_T.

The signature of neutrinos in the decays of $ZZ \to ll\nu\nu$ and $ZW \to lll'\nu$ is missing transverse energy ($\not\!\!E_T$), measured from the imbalance of E_T in the calorimeter and the escaping muon p_T (when muon candidates are present).

The next-to-leading-order (NLO) ZZ and ZW cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV are calculated by the MCFM [15] program using the CTEQ6 parton distribution functions [16]. They are $\sigma(p\bar{p} \to ZZ) = (1.39 \pm 0.10)$ pb and $\sigma(p\bar{p} \to ZW) = (3.65 \pm 0.26)$ pb.

We study events in three categories designed to encompass the main leptonic branching ratios of the ZZ and ZW decays. The first includes events with four charged leptons, which is sensitive to $ZZ \to lll'l'$ (l and $l' = e, \mu, \tau$) with a branching ratio of 1.0%. Since we only select events with electrons and/or muons, we are only sensitive to final-state taus through their subsequent decay to leptons. The second category, which includes events with three charged leptons plus $\not\!\!E_T$, consists predominantly of $ZW \to lll'\nu$ (branching ratio of 3.3%). Events from $ZZ \to lll'l'$, where one lepton is not identified, can also fall into this category. The third category includes events with two charged leptons plus $\not\!\!E_T$, which is sensitive to $ZZ \to ll\nu\nu$ (branching ratio of 4.0%) and $ZW \to lll'\nu$, where one lepton is not identified.

Our strategy is to first select events containing a Z boson and then require additional leptons and/or large $\not\!\!E_T$ in the event. The Z boson is identified by one pair of same-flavor oppositely-charged leptons (e^+e^- or $\mu^+\mu^-$) with an invariant mass between 76 GeV$/c^2$ and 106 GeV$/c^2$. The four-lepton category selects a second lepton pair using the same criteria. The three-lepton plus $\not\!\!E_T$ category selects, in addition to the Z boson, a third charged lepton with $E_T >$ 20 GeV ($p_T > 20$ GeV$/c$ for muons) and $\not\!\!E_T$ GeV. For two-lepton events, in order to reduce the significant contribution from WW boson pairs, we select Z bosons using a narrower invariant mass range of $86 < M_{ll} < 96$ GeV$/c^2$. Two additional requirements are designed to suppress the Drell-Yan background in the two-lepton category. The first requires $\not\!\!E_T$ significance ($\not\!\!E_T^{\rm sig}$) to be larger than 3 GeV$^{1/2}$, where $\not\!\!E_T^{\rm sig}$ is defined as $\not\!\!E_T/\sqrt{\sum E_T}$ and the sum is over all calorimeter towers above a given threshold. If muons are identified in the event, $\sum E_T$ is also corrected for the muon momenta. We find that $\not\!\!E_T^{\rm sig}$ is a better discriminant than $\not\!\!E_T$ in controlling the Drell-Yan background, and that the maximum expected signal significance is achieved when $\not\!\!E_T^{\rm sig}$ is at least 3 GeV$^{1/2}$. The second requirement is for $\Delta\phi$ between $\not\!\!E_T$ and the closest lepton or jet, $\Delta\phi(\not\!\!E_T$, lepton/jet), to be larger than 20°, in order to reduce the likelihood of falsely-reconstructed large $\not\!\!E_T$ due to mismeasured jets or leptons. Finally, in the two-lepton category we only consider events with zero or one jet to suppress $t\bar{t}$ background. In this analysis, jets are reconstructed using a cone of fixed radius $\Delta R = 0.4$ [17], and are counted if $E_T >$ 15 GeV and $|\eta| < 2.5$.

The main background in the four-lepton and three-lepton categories is from "fake-lepton" events, in which jets have been misidentified as leptons in $Z/W +$ jets events. The backgrounds in the two-lepton category include WW, $t\bar{t}$, Drell-Yan, and fake-lepton events.

For each of the three categories of events, the total efficiency for accepting a ZZ or ZW event can be expressed as $\epsilon_{\rm total} = \epsilon_{\rm ID} \times \epsilon_{\rm trigger} \times \epsilon_{\rm geom\text{-}kin}$, where $\epsilon_{\rm ID}$ is the efficiency for identifying the number of leptons appropriate for a given category, $\epsilon_{\rm trigger}$ is the efficiency for the event to pass the trigger requirements, and $\epsilon_{\rm geom\text{-}kin}$ is the efficiency for the leptons to fall within the geometric acceptance of the detector and for the events to pass all kinematic requirements for each signature. The total efficiencies times branching ratios are listed in Table I. The lepton identification efficiencies are measured using $Z \to ee/\mu\mu$ data.

TABLE I. The expected contributions from SM ZZ, ZW and background sources in 194 pb^{-1}, and the observed number of candidates in the data. The parentheses show the total efficiency times branching ratio for accepting ZZ or ZW events. Systematic and statistical uncertainties, and the uncertainties of the ZZ and ZW NLO cross sections, are included.

Process	4 leptons	3 leptons	2 leptons	Combined
ZZ	0.06 ± 0.01	0.13 ± 0.01	0.69 ± 0.11	0.88 ± 0.13
($\epsilon_{ZZ} \times 10^3$)	(0.22)	(0.48)	(2.56)	(3.26)
ZW	⋯	0.78 ± 0.06	0.65 ± 0.10	1.43 ± 0.16
($\epsilon_{ZW} \times 10^3$)	(⋯)	(1.10)	(0.92)	(2.02)
Total Signal	0.06 ± 0.01	0.91 ± 0.07	1.34 ± 0.21	2.31 ± 0.29
WW	⋯	⋯	0.40 ± 0.07	0.40 ± 0.07
Fake	0.01 ± 0.02	0.07 ± 0.06	0.21 ± 0.12	0.29 ± 0.16
Drell-Yan	⋯	⋯	0.31 ± 0.17	0.31 ± 0.17
$t\bar{t}$	⋯	⋯	0.02 ± 0.01	0.02 ± 0.01
Total Background	0.01 ± 0.02	0.07 ± 0.06	0.94 ± 0.22	1.02 ± 0.24
Signal + Background	0.07 ± 0.02	0.98 ± 0.09	2.28 ± 0.35	3.33 ± 0.42
Data	0	0	3	3

The $Z \rightarrow ee$ events are selected with one identified electron and a second deposition of energy in the electromagnetic calorimeter and an associated track. The $Z \rightarrow \mu\mu$ events are selected with one identified muon and a second track. The lepton pairs are required to have an invariant mass consistent with a Z and tracks of opposite charge. The unbiased lepton is used to measure the identification efficiency. The trigger efficiencies are measured using data from independent trigger paths. The geometric and kinematic efficiencies are determined using a PYTHIA event generator [18] with a GEANT-based detector simulation [19]. Table I also shows the expected numbers of ZZ and ZW events, each calculated using $\sigma \times \epsilon_{\mathrm{total}} \times \int \mathcal{L}dt$, where σ is the aforementioned NLO theoretical cross section. In each of the three categories a relatively small, but non-neglegible, fraction of the total efficiency is due to final-state tau leptons decaying to electrons and muons. Overall, we expect 2.31 ± 0.29 ZZ plus ZW events in $(194 \pm 12)\mathrm{pb}^{-1}$ of data.

The systematic uncertainties associated with the signal acceptances are dominated by the Monte Carlo simulation of $\not{E}_T^{\mathrm{sig}}$ in the two-lepton category. This uncertainty is estimated by comparing distributions of $\not{E}_T^{\mathrm{sig}}$ between data and Monte Carlo in inclusive W events, where neutrinos from the W decays produce large $\not{E}_T^{\mathrm{sig}}$. Relative to the signal acceptance, the uncertainty due to $\not{E}_T^{\mathrm{sig}}$ is 10% for ZZ and 6% for ZW. The other systematic uncertainties include those from lepton identification efficiencies (1%), trigger efficiencies (1%), the efficiency of the zero or one jet requirement (2%), dependence on different PDF's (2%), and the calorimeter energy scale and resolution (3%). The total uncertainty in the efficiency estimate is 11% for ZZ and 8% for ZW.

Backgrounds to the ZZ and ZW events are determined using a combination of data and Monte Carlo simulations. The WW, Drell-Yan, and $t\bar{t}$ background estimates are obtained using PYTHIA Monte Carlo samples with the expected numbers of events normalized to the theoretical cross sections: 12.4 pb for WW from the MCFM program, 330 pb for Drell-Yan from PYTHIA ($M(\gamma^*/Z^0) > 30\ \mathrm{GeV}/c^2$ and including a K-factor of 1.4 [20]), and 7 pb for $t\bar{t}$ [21]. A systematic uncertainty of 14% on the WW background results from the same effects that lead to the uncertainties on the ZZ and ZW acceptances. The Drell-Yan background has a 50% uncertainty from two main sources: 35% from the modeling of $\not{E}_T^{\mathrm{sig}}$, and another comparable amount from $\Delta\phi$ ($\not{E}_T$, lepton/jet). The first is estimated from the comparison of $\not{E}_T^{\mathrm{sig}}$ distributions between Drell-Yan data and Monte Carlo, and the second from the observed change in efficiency of the $\Delta\phi$ ($\not{E}_T$, lepton/jet) requirement after adjusting the jet energy scale. The $t\bar{t}$ background has a 15% uncertainty due primarily to the uncertainty in the jet energy scale.

The fake-lepton background is obtained entirely using data. First, the probability for a jet to be misidentified as an electron or muon (fake rate) is estimated from jet-triggered data samples after subtracting real leptons from W and Z decays. The lepton fake rates are averaged over four samples with increasingly harder jet E_T spectra. The observed differences between the jet samples are used to estimate the uncertainties in the lepton fake rates. The fake-lepton background is then determined by applying these fake rates to jets in lepton-triggered events which would have passed the event selection had one jet faked a lepton. This background has a 41% uncertainty, dominated by the uncertainty associated with the lepton fake rates. The backgrounds in the three event categories are summarized in Table I.

After all selection criteria we observe 3 events in the data,[1] all of them in the two-lepton plus $\not{E}_T$ category (2 ee

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[1] Another event passes all the requirements for $ZZ \rightarrow eeee$ in the four-lepton category, except for an isolation cut on one electron [22].

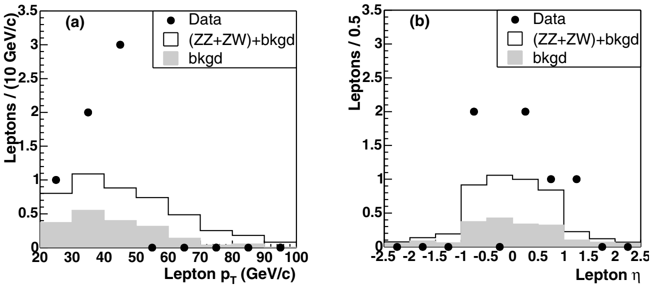

FIG. 1. Distributions of (a) lepton p_T and (b) lepton η of the candidate data events, and the expected SM contributions in the two-lepton plus $\not{E}_T$ category.

and 1 $\mu\mu$), compared to a SM signal plus background expectation of 3.33 ± 0.42 events. In Fig. 1 we present distributions of lepton p_T and η in the two-lepton plus $\not{E}_T$ category, comparing data to SM expectations. The probability for the background of 1.02 ± 0.24 events to fluctuate to give three or more events is 9%. Therefore, we set a 95% confidence level upper limit on the ZZ and ZW combined cross section by applying a Bayesian method [23] with a flat prior cross section probability above zero. Using the Poisson statistics for the data and including the assumed Gaussian uncertainties in the expected signal and background, we find that the ZZ and ZW combined cross section is less than 15.2 pb at the 95% confidence level. Using this analysis we conclude that about 1 fb^{-1} of data is needed for a 3σ measurement of the SM cross section for $ZZ + ZW$ production.

In summary, a search for ZZ and ZW production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV has been performed using the leptonic decays of the vector bosons. In a data sample corresponding to an integrated luminosity of 194 pb^{-1}, 3 candidates are found with an expected background of 1.02 ± 0.24 events. The predicted number of ZZ and ZW events is 2.31 ± 0.29. A 95% confidence level limit on the sum of the production cross sections for $p\bar{p} \to ZZ$ and $p\bar{p} \to ZW$ is measured to be 15.2 pb, consistent with the standard model prediction of 5.0 ± 0.4 pb.

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