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## Production of $W Z$ Events in $p \bar{p}$ Collisions at $\sqrt{s}=1.96 \mathrm{TeV}$ and Limits on Anomalous WWZ Couplings

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We present results from a search for $W Z$ production with subsequent decay to $\ell \nu \ell^{\prime} \overline{\ell^{\prime}}$ ( $\ell$ and $\ell^{\prime}=e$ or $\mu$ ) using $0.30 \mathrm{fb}^{-1}$ of data collected by the $\mathrm{D} \varnothing$ experiment between 2002 and 2004 at the Tevatron. Three events with $W Z$ decay characteristics are observed. With an estimated background of $0.71 \pm 0.08$ events, we measure the $W Z$ production cross section to be $4.5_{-2.6}^{+3.8} \mathrm{pb}$, with a $95 \%$ C.L. upper limit of 13.3 pb . The $95 \%$ C.L. limits for anomalous $W W Z$ couplings are found to be $-2.0<\Delta \kappa_{Z}<2.4$ for form factor scale $\Lambda=1 \mathrm{TeV}$, and $-0.48<\lambda_{Z}<0.48$ and $-0.49<\Delta g_{1}^{Z}<0.66$ for $\Lambda=1.5 \mathrm{TeV}$.

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The $S U(2)_{L} \otimes U(1)_{Y}$ structure of the standard model
(SM) Lagrangian implies that the electroweak gauge
bosons $W$ and $Z$ interact with one another through trilinear and quartic vertices. As a consequence, the production cross section $\sigma(p \bar{p} \rightarrow W Z)$ depends on the $W W Z$ gauge coupling shown in Fig. 112. The SM predicts that the strength of that coupling is $-e \cot \theta_{W}$, where $e$ is the electric charge and $\theta_{W}$ is the weak mixing angle. More generally, excursions of the $W W Z$ interactions from the SM can be described by an effective Lagrangian with parameters $g_{1}^{Z}, \lambda_{Z}$ and $\kappa_{Z}$ [1]. This effective Lagrangian reduces to the SM Lagrangian when the couplings are set to their SM values $g_{1}^{Z}=\kappa_{Z}=1$ and $\lambda_{Z}=0$. Non-SM values of these couplings will increase $\sigma_{W Z}$. Therefore a measurement of the $W Z$ production cross section provides a sensitive test of the strength of the $W W Z$ interaction. This test also probes for low-energy manifestations of new physics, appearing at a higher mass scale, that complements searches to be carried out with future higher-energy accelerators.


FIG. 1: Tree-level diagrams for $W Z$ production in $p \bar{p}$ collisions. Diagram (a) contains the $W W Z$ trilinear gauge coupling vertex.

A model-independent test for anomalous trilinear boson couplings using $\sigma_{W Z}$ is unique among vector boson pair production processes in that $W Z$ diagrams contain only $W W Z$, and not $W W \gamma$, vertices. Anomalous trilinear gauge boson coupling limits set using characteristics of $W^{+} W^{-}$production [2, 3, [4, 5, 6, 7, [8] are sensitive to both the $W W \gamma$ and $W W Z$ couplings and must make an assumption [7, 9] relating them. Furthermore, as the $W^{ \pm} Z$ production process is unavailable at $e^{+} e^{-}$colliders 3, 4, 5, 6], a hadron collider such as the Tevatron at Fermilab provides an unique opportunity for measurement of the $W W Z$ coupling.

Using $90 \mathrm{pb}^{-1}$ of $p \bar{p}$ collisions collected at $\sqrt{s}=1.8$ TeV during Run I (1992-1996), the D $\emptyset$ Collaboration established that $\sigma_{W Z}<47 \mathrm{pb}$ at $95 \%$ C.L. From these data, $\mathrm{D} \emptyset$ also set $95 \%$ C.L. limits $\left|g_{1}^{Z}-1\right|<1.63$ and $\left|\lambda_{Z}\right|<1.42$ for a form factor scale 1] $\Lambda=1 \mathrm{TeV}$ [8]. With a higher center-of-mass energy $(\sqrt{s}=1.96 \mathrm{TeV})$ expected to increase the SM $W Z$ production cross section to $3.7 \pm 0.1 \mathrm{pb}$ [10], more luminosity, and improved detec-
tors, the Run II Tevatron program opens a new window for studies of $W Z$ production. The CDF Collaboration recently announced a 15.2 pb upper limit at the $95 \%$ C.L. on the combined cross section for $W Z$ and $Z Z$ production [11].

We present the results of a search for $W Z$ production with "trilepton" final states $\ell \nu \ell^{\prime} \bar{\ell}^{\prime}\left(\ell\right.$ and $\ell^{\prime}=e$ or $\mu$ ) using data collected by the D $\emptyset$ experiment from 2002-2004 at $\sqrt{s}=1.96 \mathrm{TeV}$. Requiring three isolated high transverse momentum ( $p_{T}$ ) charged leptons and large missing transverse energy $\left(E_{T}\right)$, to indicate the presence of a neutrino, strongly suppresses backgrounds which mimic the WZ signal. However, branching ratios sum to only $1.5 \%$ for trilepton final states ( $\mu \nu e e, ~ e \nu \mu \mu, e \nu e e$ and $\mu \nu \mu \mu$ ). The $W Z$ signal that we seek is distinct but rare.

The D $\emptyset$ detector 12, 13] comprises several subdetectors and a trigger and data acquisition system. The central-tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT) located within a 2 T superconducting solenoidal magnet. The SMT and CFT measure the locations of the collisions and the momenta of charged particles. The energies of electrons, photons, and hadrons, and the amount of $E_{T}$, is measured in three uranium/liquid-argon calorimeters, each housed in a separate cryostat [12]: a central section (CC) covering $|\eta| \leq 1.1$ and two end calorimeters (EC) extending coverage to $|\eta| \leq 4.2$, where $\eta$ is the pseudorapidity. Scintillators between the CC and EC cryostats provide sampling of developing showers for $1.1<|\eta|<1.4$. A muon system 13] resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers behind the toroids. A three level trigger and data acquisition system uses information from the subdetectors to select $\approx 50 \mathrm{~Hz}$ of collisions for further "offline" reconstruction.

With at least three high- $p_{T}$ charged leptons in the candidate events, the overall trigger efficiency for the $W Z$ signal is nearly $100 \%$. Integrated luminosities for the evee, $\mu \nu e e, ~ e \nu \mu \mu$ and $\mu \nu \mu \mu$ final states are $320 \mathrm{pb}^{-1}$, $290 \mathrm{pb}^{-1}, 280 \mathrm{pb}^{-1}$, and $290 \mathrm{pb}^{-1}$, respectively, with a common uncertainty of $6.5 \%$ 14].

Electrons from $W$ and $Z$ boson decays are identified by their pattern of spatially isolated energy deposition in the calorimeter and by the presence of a matching track in the central tracking system. The transverse energy of an electron, measured in the calorimeter, must satisfy $E_{T}>15 \mathrm{GeV}$.

A muon is identified by a pattern of hits in the scintillation counter and drift chamber system and must have a matching central track. Muon isolation is determined from an examination of the energy in calorimeter cells and the momenta of any additional tracks around the muon. Muons must have $p_{T}>15 \mathrm{GeV} / c$.

Missing transverse energy is determined from the negative of the vector sum of transverse energies of the


FIG. 2: $E_{T}$ versus dilepton invariant mass distribution for $\sim 200 \mathrm{fb}^{-1}$ of simulated $W Z \rightarrow \mu \nu \mu \mu$ events (light grey) and for expected $Z+$ jet(s) background events (dark grey). The central box shows the event selection criteria. The two $W Z \rightarrow$ $\mu \nu \mu \mu$ candidates are indicated as stars. The corresponding figures are similar in the channels where the $Z$ boson decays to electrons. There is one candidate for the $W Z \rightarrow$ evee decay channel.
calorimeter cells, adjusted for the presence of any muons identified above.

The $W Z$ event selection requires at least three charged leptons that originate from a common interaction vertex and survive the electron or muon identification criteria outlined above. To associate reconstructed tracks with leptons unambiguously, they are required to be spatially separated. To select $Z$ bosons and suppress backgrounds further, the invariant mass of a like-flavor lepton pair must fall within $71 \mathrm{GeV} / c^{2}$ to $111 \mathrm{GeV} / c^{2}$ for $e^{+} e^{-}$ events, and $51 \mathrm{GeV} / c^{2}$ to $131 \mathrm{GeV} / c^{2}$ for $\mu^{+} \mu^{-}$events, where the different mass windows correspond to the respective resolutions of the calorimeter and the central tracker. For the evee and $\mu \nu \mu \mu$ channels, the lepton pair with invariant mass closest to the $Z$ boson mass is chosen as the $Z$ candidate. The $E_{T}$ is required to be greater than 20 GeV , consistent with a $W$ boson decay. The transverse mass, although not used as a selection criterion, is calculated from the $p_{T}$ of the unpaired third lepton and the $E_{T}$. Finally, to reject background from $t \bar{t}$ events, the vector sum of the transverse energies in all calorimeter cells, excluding the leptons, must be less than 50 GeV . Figure 2 shows the comparison of the dilepton invariant mass and $E_{T}$ distributions expected for $W Z \rightarrow \mu \nu \mu \mu$ events to the background from $Z+$ jet(s) events.

Applying all selection requirements leaves one evee and two $\mu \nu \mu \mu$ candidates. Table $\rrbracket$ summarizes the kinematic properties of these events.

Signal acceptances include geometric and kinematic effects and are obtained using Monte Carlo samples produced with the PYTHIA event generator 16] followed by the GEANT-based 17] D $\varnothing$ detector-simulation pro-
gram. Acceptances are calculated by counting the number of events that pass all selection criteria, except the lepton identification and track-matching requirements. The results are $0.283 \pm 0.009,0.279 \pm 0.008,0.287 \pm 0.009$ and $0.294 \pm 0.008$ for evee, $\mu \nu e e, e \nu \mu \mu$ and $\mu \nu \mu \mu$ final states, respectively.

Lepton-identification and central-track-matching efficiencies are estimated using samples of $Z \rightarrow e^{+} e^{-}$and $Z \rightarrow \mu^{+} \mu^{-}$events. One of the leptons from the $Z$ boson decay is required to pass all lepton selection requirements. The other lepton is tested as to whether it passes the selection criteria. Both identification efficiencies and track-matching efficiencies are determined as functions of $p_{T}$ and $\eta$. Average identification efficiencies are $0.929 \pm 0.013$ and $0.965 \pm 0.008$ for CC and EC electrons, respectively, and $0.940 \pm 0.002$ for muons. Track-matching efficiencies are $0.817 \pm 0.002$ for CC electrons, $0.674 \pm 0.006$ for EC electrons, and $0.950 \pm 0.002$ for muons. These efficiencies are folded into the WZ MC events used for acceptance calculations. The overall $W Z$ acceptance times detection efficiencies are (10.3 $\pm 1.5$ )\%, $(11.7 \pm 0.8) \%,(13.9 \pm 1.3) \%$, and $(16.3 \pm 1.8) \%$ for evee, $\mu \nu e e, e \nu \mu \mu$ and $\mu \nu \mu \mu$, respectively.

From the SM prediction for $\sigma_{W Z}$ and the leptonic branching fractions of the $W$ and $Z$ bosons [18], we expect $0.44 \pm 0.07,0.45 \pm 0.04,0.53 \pm 0.06,0.62 \pm 0.08 \mathrm{WZ}$ events for the evee, $\mu \nu e e, e \nu \mu \mu$, and $\mu \nu \mu \mu$ final states, respectively. Quoted uncertainties include statistical and systematic contributions, as well as the $6.5 \%$ uncertainty in the integrated luminosity.

Among SM processes, $W Z$ production is the dominant mechanism that results in events with a final state that includes three isolated leptons with large transverse momentum and with large $E_{T}$. The main backgrounds to $W Z$ production come from $Z+X(X=$ hadronic jets, $\gamma$, or $Z$ ) events. In $Z+$ jet(s) events, a jet may be misidentified as an additional lepton. This background is estimated from data as follows. Events are selected using the same criteria as for the $W Z$ sample, except that the requirement of the third lepton is dropped. The resulting "dilepton + jet(s)" sample includes $e e+$ jets, $\mu \mu+$ jets and $e \mu+$ jets events. Probabilities for hadronic jets to mimic electrons and muons are determined, using multijet data, as a function of jet $E_{T}$ and jet $\eta$. Applying the misidentification probabilities to jets in the dilepton + jet(s) events yields the total background, estimated to be $0.35 \pm 0.02$ events. In $Z+\gamma$ events, a $\gamma$ may be converted to electrons or randomly match a charged-particle track in the detector causing it to be misidentified as an electron. This background process only contributes to the $e \nu \mu \mu$ and evee final states. Though we have identified hundreds of $Z+\gamma$ events [19], we found the probability for a photon to be misidentified as an electron is $\sim 2 \%$. As these events do not typically have large $E_{T}$, the number which mimic the $W Z$ signal is small. We estimate it as $0.145 \pm 0.020$ events. The backgrounds from $Z Z$ and $t \bar{t}$

TABLE I: Kinematic properties of the three $W Z$ candidates. Provided are the momentum four-vectors for the two leptons which constitute the $Z$ boson candidate, the invariant mass formed from those two leptons, the momentum 4 -vector of the charged lepton from the $W$ boson decay, the components of the $E_{T}$, and the transverse mass computed from the third lepton and the $\mathscr{E}_{T}$ [15]. The units are $\mathrm{GeV}, \mathrm{GeV} / c, \mathrm{GeV} / c^{2}$, as appropriate.

| Final | $\ell_{Z}$ |  |  |  | $\ell_{Z}$ |  |  |  |  | $\ell_{W}$ |  |  |  | $\dot{H}_{T x}$ | $E_{T y}$ | $m_{T}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| State | $p_{x}$ | $p_{y}$ | $p_{z}$ | $E$ | $p_{x}$ | $p_{y}$ | $p_{z}$ | $E$ | $m_{\ell \ell}$ | $p_{x}$ | $p_{y}$ | $p_{z}$ | $E$ |  |  |  |
| evee | -47.3 | -25.9 | 292 | 297 | 13.3 | 37.6 | 111 | 118 | 91.9 | 45.3 | -32.1 | -16.5 | 57.9 | -19.6 | -23.5 | 72.3 |
| $\mu \nu \mu \mu$ | 24.5 | 11.6 | 29.7 | 40.2 | -38.7 | -12.4 | -17.1 | 44.1 | 82.1 | -19.3 | -16.7 | 101 | 105 | 24.1 | 19.8 | 56.4 |
| $\mu \nu \mu \mu$ | -15.1 | 19.9 | 24.4 | 35.0 | 20.2 | -42.5 | 57.1 | 74.0 | 68.5 | -21.9 | -5.90 | -16.4 | 28.0 | 34.8 | 25.4 | 62.5 |

production are estimated using Monte Carlo methods to be $0.20 \pm 0.07$ and $0.01 \pm 0.01$ events, respectively. Other sources of background are found to be negligible. The total background is estimated to be $0.71 \pm 0.08$ events.

The combination of expected $W Z$ signal and background is consistent with having observed three $W Z$ candidates. The probability for a background of 0.71 events alone to fluctuate to three or more candidates is $3.5 \%$. Following the method described in Refs. 18] and [20], we use a maximum likelihood technique to obtain $\sigma_{W Z}=4.5_{-2.6}^{+3.8} \mathrm{pb}$ and calculate the $95 \%$ C.L. upper limit $\sigma_{W Z}<13.3 \mathrm{pb}$ for $\sqrt{s}=1.96 \mathrm{TeV}$.

As $\sigma_{W Z}$ is consistent with the SM, we can extract limits on anomalous $W W Z$ couplings. Monte Carlo $W Z \rightarrow$ trilepton events are generated 21] at each point in a twodimensional grid of anomalous couplings. We used a parameterized detector simulation to model the detector response and applied the same selection criteria that were applied to the data to determine the predicted $W Z$ signal at each grid point. These predictions are combined with the estimated background and compared with the three observed trilepton candidates to construct a likelihood function $L$. Analyses of contours of $L$ then permits limits to be set on $\lambda_{Z}, \Delta g_{1}^{Z}$ and $\Delta \kappa_{Z}$, both individually and in pairs, where $\Delta \kappa_{Z} \equiv \kappa_{Z}-1$ and $\Delta g_{1}^{Z} \equiv g_{1}^{Z}-1$. Table 【I lists one-dimensional $95 \%$ C.L. limits on $\lambda_{Z}, \Delta g_{1}^{Z}$ and $\Delta \kappa_{Z}$ with $\Lambda=1 \mathrm{TeV}$ or $\Lambda=1.5 \mathrm{TeV}$. Figure 3 shows two-dimensional $95 \%$ C.L. contour limits for $\Lambda=1.5 \mathrm{TeV}$ with the assumption of $S U(2)_{L} \otimes U(1)_{Y}$ gauge invariance relating the couplings 7]. The values of the form factors are chosen such that the coupling limit contours are within the contours provided by $S$-matrix unitarity [22].

In summary, we searched for $W Z$ production in $p \bar{p}$ collisions at $\sqrt{s}=1.96 \mathrm{TeV}$. In a sample of $0.30 \mathrm{fb}^{-1}$, three candidate events were found with an expected background of $0.71 \pm 0.08$ events. The $95 \%$ C.L. upper limit for the $W Z$ cross section is 13.3 pb . Interpreting the candidates as a combination of $W Z$ signal plus background, we find $\sigma_{W Z}=4.5_{-2.6}^{+3.8} \mathrm{pb}$ and provide the first measurement of the $W Z$ production cross section at hadron colliders. We used the results of the search to obtain the tightest available limits on anomalous $W W Z$ couplings derived from a $W Z$ final state. Furthermore, these are


FIG. 3: Two-dimensional coupling limits (inner contour) on $\lambda_{Z}$ vs. $\Delta g_{1}^{Z}$ at $95 \%$ C.L. for $\Lambda=1.5 \mathrm{TeV}$ under the assumptions of Ref. [7], which reduce to $\Delta \kappa_{Z}=\Delta g_{1}^{Z}$ for $W Z$ production. The outer contour is the limit from $S$-matrix unitarity.
the most restrictive model-independent $W W Z$ anomalous coupling limits available and represent an improvement by a factor of three over the previous best results [8].

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[^0]TABLE II: One-dimensional $95 \%$ C.L. intervals on $\lambda_{Z}, \Delta g_{1}^{Z}$, and $\Delta \kappa_{Z}$. In the missing last entry, the $95 \%$ C.L. limit exceeded the bounds from $S$-matrix unitarity. The assumption $\Delta g_{1}^{Z}=\Delta \kappa_{Z}$ is equivalent to that used in Ref. [7].

| Condition | $\Lambda=1 \mathrm{TeV}$ | $\Lambda=1.5 \mathrm{TeV}$ |
| :---: | :---: | :---: |
| $\Delta g_{1}^{Z}=\Delta \kappa_{Z}=0$ | $-0.53<\lambda_{Z}<0.56$ | $-0.48<\lambda_{Z}<0.48$ |
| $\lambda_{Z}=\Delta \kappa_{Z}=0$ | $-0.57<\Delta g_{1}^{Z}<0.76$ | $-0.49<\Delta g_{1}^{Z}<0.66$ |
| $\lambda_{Z}=0$ | $-0.49<\Delta g_{1}^{Z}=\Delta \kappa_{Z}<0.66$ | $-0.43<\Delta g_{1}^{Z}=\Delta \kappa_{Z}<0.57$ |
| $\lambda_{Z}=\Delta g_{1}^{Z}=0$ | $-2.0<\Delta \kappa_{Z}<2.4$ | - |

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