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

We present results from a search for $WZ$ production with subsequent decay to $f\nu\bar{f}$ using $0.30 \pm 0.11 \text{ fb}^{-1}$ of data collected by the DØ experiment between 2002 and 2004 at the Tevatron. Three events with $WZ$ decay characteristics are observed. With an estimated background of $0.71 \pm 0.08$ events, we measure the $WZ$ production cross section to be $4.55^{+3.8}_{-2.6} \text{ pb}$, with a 95% C.L. upper limit of $13.3 \text{ pb}$. The 95% C.L. limits for anomalous $WWZ$ couplings are found to be $-2.0 < \Delta \kappa_Z < 2.4$ for form factor scale $\Lambda = 1 \text{ TeV}$, and $-0.48 < \lambda_Z < 0.48$ and $-0.49 < \Delta g_1^2 < 0.66$ for $\Lambda = 1.5 \text{ TeV}$.

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The $SU(2)_L \otimes U(1)_Y$ 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 $\sigma(pp \rightarrow WZ)$ depends on the WWZ gauge coupling shown in Fig. 1a. The SM predicts that the strength of that coupling is $-e \cos \theta_W$, where $e$ is the electric charge and $\theta_W$ is the weak mixing angle. More generally, excursions of the WWZ interactions from the SM can be described by an effective Lagrangian with parameters $g_1^W$, $\lambda_Z$, and $\kappa_Z$ [1]. This effective Lagrangian reduces to the SM Lagrangian when the couplings are set to their SM values $g_1^W = \kappa_Z = 1$ and $\lambda_Z = 0$. Non-SM values of these couplings will increase $\sigma_{WZ}$. Therefore a measurement of the WWZ production cross section provides a sensitive test of the strength of the WWZ 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.

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

Using $90 \text{ pb}^{-1}$ of $p\bar{p}$ collisions collected at $\sqrt{s} = 1.8$ TeV during Run I (1992–1996), the DØ Collaboration established that $\sigma_{WZ} < 47 \text{ pb}$ at 95% C.L. From these data, DØ also set 95% C.L. limits $|g_1^W - 1| < 1.63$ and $|\lambda_Z| < 1.42$ for a form factor scale [1]. A lower center-of-mass energy ($\sqrt{s} = 1.96$ TeV) expected to increase the SM WWZ production cross section to $3.7 \pm 0.1 \text{ pb}$ [10], more luminosity, and improved detectors, the Run II Tevatron program opens a new window for studies of WWZ production. The CDF Collaboration recently announced a 15.2 pb upper limit at the 95% C.L. on the combined cross section for WW and ZZ production [11].

We present the results of a search for WWZ production with “trilepton” final states $\ell\ell'\ell'$ ($\ell$ and $\ell' = e$ or $\mu$) using data collected by the DØ experiment from 2002–2004 at $\sqrt{s} = 1.96$ TeV. Requiring three isolated high transverse momentum $(p_T)$ charged leptons and large missing transverse energy ($E_T^\text{miss}$), to indicate the presence of a neutrino, strongly suppresses backgrounds which mimic the WWZ signal. However, branching ratios sum to only 1.5% for trilepton final states ($\ell\ell'\nu\nu$, $\ell\ell'\mu\nu$, and $\ell_1\ell_2\nu\nu$). The WWZ signal that we seek is distinct but rare.

The DØ 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 $E_T^\text{miss}$, 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 $\approx 50$ 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 WWZ signal is nearly 100%. Integrated luminosities for the $\ell\ell\nu\nu$, $\ell\ell\mu\nu$, and $\ell\ell\nu\nu$ final states are 320 pb$^{-1}$, 290 pb$^{-1}$, 280 pb$^{-1}$, and 290 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 $E_T > 15$ 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 $p_T > 15$ GeV/c.

Missing transverse energy is determined from the negative of the vector sum of transverse energies of the
Figure 2: $E_T$ versus dilepton invariant mass distribution for $\sim 200$ fb$^{-1}$ of simulated $WZ \rightarrow \mu\mu\mu\nu$ events (light grey) and for expected $Z + \text{jet(s)}$ background events (dark grey). The central box shows the event selection criteria. The two $WZ \rightarrow \mu\mu\mu\nu$ 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 $WZ \rightarrow eee\nu$ decay channel.

calorimeter cells, adjusted for the presence of any muons identified above.

The $WZ$ 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 $71 \text{ GeV}/c^2$ to $111 \text{ GeV}/c^2$ for $e^+e^-$ events, and $51 \text{ GeV}/c^2$ to $131 \text{ GeV}/c^2$ for $\mu^+\mu^-$ events, where the different mass windows correspond to the respective resolutions of the calorimeter and the central tracker. For the $e\mu\nu$ and $\mu\mu\mu\nu$ 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 $WZ \rightarrow \mu\mu\nu$ events to the background from $Z + \text{jet(s)}$ events.

Applying all selection requirements leaves one $e\mu\nu$ and two $\mu\mu\nu$ candidates. Table I 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] DØ detector-simulation program. 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 $e\mu\nu$, $\mu\nu\nu$, $e\mu\mu\nu$ and $\mu\mu\mu\nu$ 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 $WZ$ 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 $e\mu\nu$, $\mu\nu\nu$, $e\mu\mu\nu$, and $\mu\mu\mu\nu$, respectively.

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

Among SM processes, $WZ$ 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 $WZ$ production come from $Z + X (X=\text{hadronic jets, } \gamma, \text{ or } Z)$ events. $Z + \text{jet(s)}$ 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 $WZ$ sample, except that the requirement of the third lepton is dropped. The resulting “dilepton + jet(s)” sample includes $ee + \text{jets}$, $\mu\mu + \text{jets}$ and $e\mu + \text{jets}$ events. Probabilities for hadronic jets to mimic electrons and muons are determined, using multi-jet 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 $e\mu\mu\nu$ and $e\mu\nu$ 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 $WZ$ signal is small. We estimate it as $0.145 \pm 0.020$ events. The backgrounds from $ZZ$ and $t\bar{t}$
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 $WZ$ signal and background is consistent with having observed three $WZ$ 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 $\sigma_{WZ} = 4.5^{+3.8}_{-2.6}$ pb and calculate the 95% C.L. upper limit $\sigma_{WZ} < 13.3$ pb for $\sqrt{s} = 1.96$ TeV.

As $\sigma_{WZ}$ is consistent with the SM, we can extract limits on anomalous $WZ$ couplings. Monte Carlo $WZ \to$ trilepton events are generated [21] at each point in a two-dimensional 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 $WZ$ 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 $\lambda_Z$, $\Delta g_1^Z$, $\Delta g_2^Z$ and $\Delta \kappa_Z$, both individually and in pairs, where $\Delta \kappa_Z \equiv \kappa_Z - 1$ and $\Delta g_i^Z \equiv g_i^Z - 1$. Table II lists one-dimensional 95% C.L. limits on $\lambda_Z$, $\Delta g_1^Z$ and $\Delta \kappa_Z$ with $\Lambda = -1$ TeV or $\Lambda = 1.5$ TeV. Figure 3 shows two-dimensional 95% C.L. contour limits for $\Lambda = 1.5$ TeV with the assumption of $SU(2)_L \otimes U(1)_Y$ 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 $WZ$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. In a sample of 0.30 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 $WZ$ cross section is 13.3 pb. Interpreting the candidates as a combination of $WZ$ signal plus background, we find $\sigma_{WZ} = 4.5^{+3.8}_{-2.6}$ pb and provide the first measurement of the $WZ$ production cross section at hadron colliders. We used the results of the search to obtain the tightest available limits on anomalous $WZ$ couplings derived from a $WZ$ final state. Furthermore, these are the most restrictive model-independent $WZ$ anomalous coupling limits available and represent an improvement by a factor of three over the previous best results [8].

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[2] Visitor from University of Zurich, Zurich, Switzerland.
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].

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\Lambda = 1$ TeV</th>
<th>$\Lambda = 1.5$ TeV</th>
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<tbody>
<tr>
<td>$\Delta g_1^Z = \Delta \kappa_Z = 0$</td>
<td>$-0.53 &lt; \lambda_Z &lt; 0.56$</td>
<td>$-0.48 &lt; \lambda_Z &lt; 0.48$</td>
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<tr>
<td>$\lambda_Z = \Delta \kappa_Z = 0$</td>
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<td>$-0.49 &lt; \Delta g_1^Z &lt; 0.66$</td>
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<tr>
<td>$\lambda_Z = 0$</td>
<td>$-0.49 &lt; \Delta g_1^Z = \Delta \kappa_Z &lt; 0.66$</td>
<td>$-0.43 &lt; \Delta g_1^Z = \Delta \kappa_Z &lt; 0.57$</td>
</tr>
<tr>
<td>$\lambda_Z = \Delta \kappa_Z = 0$</td>
<td>$-2.0 &lt; \Delta \kappa_Z &lt; 2.4$</td>
<td>–</td>
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</tbody>
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Nucl. Phys. B282, 253 (1987). Since tree-level unitarity restricts the anomalous couplings to their SM values at asymptotically high energies, each of the couplings must be modified by a form factor, e.g., $\lambda_Z(s) = \lambda_Z/(1 + s/\Lambda^2)^2$, where $s$ is the square of the invariant mass of the $WZ$ system and $\Lambda$ is the form factor scale.


[7] LEP Electroweak Working Group, D. Abbaneo et al., hep-ex/0412015. They parameterize $WWZ$ couplings in terms of the $WW\gamma$ couplings: $\Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa_\gamma \tan^2 \theta_W$ and $\lambda_Z = \lambda_\gamma$.

[8] DØ Collaboration, B. Abbott et al., Phys. Rev. D 60 072002 (1999). This paper contains both a description of a search for $WZ \rightarrow$ trileptons with anomalous $WZ\gamma$ coupling limits and a search for non-standard-model $WW \rightarrow WZ \rightarrow \ell\nu$ jet jet production with limits on anomalous $WW\gamma$ and $WZ\gamma$ couplings.

[9] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. D 48, 2182 (1993). They parameterize $WZX$ couplings in terms of the $WW\gamma$ couplings: $\Delta \kappa_Z = \Delta \kappa_\gamma (1 - \tan^2 \theta_W)/2$, $\Delta g_1^Z = \Delta \kappa_\gamma/(2 \cos^2 \theta_W)$ and $\lambda_Z = \lambda_\gamma$.


[15] We use a right-handed coordinate system with $\hat{z}$ pointing in the direction of the proton beam and $\hat{y}$ pointing upwards.


