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


(DO Collaboration)
We present results from a search for $WZ$ production with subsequent decay to $\ell\nu\ell'\nu'$ ($\ell$ and $\ell' = e$ or $\mu$) using $0.30 \, \text{fb}^{-1}$ 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 $4.5^{+2.6}_{-1.5} \, \text{pb}$, 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 $-2.0 < \lambda_{3} < 2.4$ for form factor scale $\Lambda = 1 \, \text{TeV}$, and $-0.48 < \lambda_{Z} < 0.48$ and $-0.49 < \Delta \eta_{Z}^{2} < 0.66$ for $\Lambda = 1.5 \, \text{TeV}$.

PACS numbers: 14.70.Fm, 13.40.Em, 13.85.Rm, 14.70.Hp

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 $-e\cot \theta_W$, 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 $g_1^2$, $\lambda_Z$ and $\kappa_Z$ [1]. This effective Lagrangian reduces to the SM Lagrangian when the couplings are set to their SM values $g_1^2 = \kappa_Z = 1$ and $\lambda_Z = 0$. Non-SM values of these couplings will increase $\sigma_{WZ}$. Therefore a measurement of the $WZ$ 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 $WZ$ diagrams contain only $WW$, and not $WW\gamma$, 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 $WW\gamma$ 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, 4, 5, 6], a hadron collider such as the Tevatron at Fermilab provides an unique opportunity for measurement of the $WWZ$ coupling.

Using 90 pb$^{-1}$ of $pp$ collisions collected at $\sqrt{s} = 1.8$ TeV during Run I (1992–1996), the D0 Collaboration established that $\sigma_{WZ} < 47$ pb at 95% C.L. From these data, D0 also set 95% C.L. limits $|g_1^2| < 1.63$ and $|\lambda_Z| < 1.42$ for a form factor scale [1] $\Lambda = 1$ TeV [8]. With a higher center-of-mass energy ($\sqrt{s} = 1.96$ TeV) expected to increase the SM $WZ$ production cross section to $3.7 \pm 0.1$ pb [10], more luminosity, and improved detectors, the Run II Tevatron program opens a new window for studies of $WZ$ production. The CDF Collaboration recently announced a 15.2 pb upper limit at the 95% C.L. on the combined cross section for $WZ$ and $ZZ$ production [11].

We present the results of a search for $WZ$ production with “trilepton” final states $\ell\ell'\ell'$ ($\ell$ and $\ell' = e$ or $\mu$) using data collected by the D0 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 ($E_T$), 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 ($\mu\mu\mu$, $\mu\nu\mu$, $\mu e e$ and $\nu\nu\nu$). The $WZ$ signal that we seek is distinct but rare.

The D0 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 $|\eta| < 1.1$ and two end calorimeters (EC) extending coverage to $|\eta| < 4.2$, 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 $WZ$ signal is nearly 100%. Integrated luminosities for $\mu\mu\mu$, $\nu\nu\nu$, $e\nu\nu$ and $e\nu\nu$ 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
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 $e\nu\nu$ and $\mu\nu\nu$ 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 $20 \text{ GeV}$, 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 $50 \text{ GeV}$.

Figure 2 shows the comparison of the dilepton invariant mass and $E_T$ distributions expected for $WZ \rightarrow \mu\nu\mu$ events to the background from $Z + jet(s)$ events.

Applying all selection requirements leaves one $e\nu\nu\nu$ and two $\mu\nu\nu\nu$ 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 $e\nu\nu$, $\mu\nu\nu$, $e\nu\nu\nu$ and $\mu\nu\nu\nu$ 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 $e\nu\nu$, $\mu\nu\nu$, $e\nu\nu\nu$, and $\mu\nu\nu\nu$ final states, respectively.

From the SM prediction for $\sigma_{WZ}$ and the leptonic branching fractions of the W and Z bosons [18], we expect $0.44 \pm 0.07$, $0.45 \pm 0.04$, $0.53 \pm 0.06$, and $0.62 \pm 0.08$ WZ events for the $e\nu\nu$, $\mu\nu\nu$, $e\nu\nu\nu$, and $\mu\nu\nu\nu$ 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 $Z + X$ ($X=$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 WZ sample, except that the requirement of the third lepton is dropped. The resulting “dilepton + jet(s)” sample includes $ee + jets$, $\mu\mu + jets$ and $e\mu + jets$ 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.

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 $t\bar{t}$
TABLE I: Kinematic properties of the three WZ 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 \( \ell_T \), and the transverse mass computed from the third lepton and the \( \ell_T \) [15]. The units are GeV, GeV/c, GeV/c^2, as appropriate.

| Final State | \( p_x \) | \( p_y \) | \( p_z \) | \( E \) | \( \ell_Z \) | \( p_x \) | \( p_y \) | \( p_z \) | \( E \) | \( m_{\ell\ell} \) | \( \ell_w \) | \( p_x \) | \( p_y \) | \( p_z \) | \( E \) | \( E_{T_x} \) | \( E_{T_y} \) | \( m_T \) |
|------------|-------|-------|-------|-----|-------|-------|-------|-------|-----|----------|-------|-------|-------|-------|----------|----------|-------|
| \( e\mu e\mu \) | -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 |
| \( \mu\mu e\mu \) | 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 |
| \( \mu\mu e\mu \) | -15.1 | 19.9 | 24.4 | 35.0 | 20.2 | -42.5 | 57.1 | 74.0 | 68.5 | -21.9 | -5.90 | -16.4 | 44.1 | 82.1 | -19.3 | -16.7 |

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 WWZ couplings. Monte Carlo WZ \( \rightarrow \) 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 \( \lambda_\omega, \Delta g_\omega^Z, \) and \( \Delta \kappa_\omega \), both individually and in pairs, where \( \Delta \kappa_\omega \equiv \kappa_\omega - 1 \) and \( \Delta g_\omega^Z \equiv g_\omega^Z - 1 \). Table II lists one-dimensional 95% C.L. limits for \( \lambda_\omega, \Delta g_\omega^Z, \) and \( \Delta \kappa_\omega \) with \( \Lambda = 1 \) TeV and \( \Lambda = 1.5 \) 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 \( pp \) 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 WWZ couplings derived from a WZ final state. Furthermore, these are the most restrictive model-independent WWZ anomalous coupling limits available and represent an improvement by a factor of three over the previous best results [8].

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA), CEA and CNRS/IN2P3 (France), FASI, Rosatom and RFBR (Russia), CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), DAE and DST (India), Colciencias (Colombia), CONACyT (Mexico), KRF (Korea), CONICET and UBACyT (Argentina), FOM (The Netherlands), PPARC (United Kingdom), MSMT (Czech Republic), CRC Program, CFI, NSERC and WestGrid Project (Canada), BMBF and DFG (Germany), SFI (Ireland), A.P. Sloan Foundation, Research Corporation, Texas Advanced Research Program, Alexander von Humboldt Foundation, and the Marie Curie Fellowships.

\[ \text{FIG. 3: Two-dimensional coupling limits (inner contour) on } \lambda_\omega \text{ vs. } \Delta g_\omega^Z \text{ at } 95\% \text{ C.L. for } \Lambda = 1.5 \text{ TeV under the assumptions of Ref. [7], which reduce to } \Delta \kappa_\omega = \Delta g_\omega^Z \text{ for WZ production. The outer contour is the limit from S-matrix unitarity.} \]

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

TABLE II: One-dimensional 95% C.L. intervals on $\Delta g_{Z}^{Z}$, and $\Delta \kappa_{Z}$. In the missing last entry, the 95% C.L. limit exceeded the bounds from S-matrix unitarity. The assumption $\Delta g_{Z}^{Z} = \Delta \kappa_{Z}$ 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>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g_{Z}^{Z} = \Delta \kappa_{Z} = 0$</td>
<td>$-0.53 &lt; \lambda_{Z} &lt; 0.56$</td>
<td>$-0.48 &lt; \lambda_{Z} &lt; 0.48$</td>
</tr>
<tr>
<td>$\lambda_{Z} = \Delta \kappa_{Z} = 0$</td>
<td>$-0.57 &lt; \Delta g_{Z}^{Z} &lt; 0.76$</td>
<td>$-0.49 &lt; \Delta g_{Z}^{Z} &lt; 0.66$</td>
</tr>
<tr>
<td>$\lambda_{Z} = 0$</td>
<td>$-0.49 &lt; \Delta g_{Z}^{Z} = \Delta \kappa_{Z} &lt; 0.66$</td>
<td>$-0.43 &lt; \Delta g_{Z}^{Z} = \Delta \kappa_{Z} &lt; 0.57$</td>
</tr>
<tr>
<td>$\lambda_{Z} = \Delta g_{Z}^{Z} = 0$</td>
<td>$-2.0 &lt; \Delta \kappa_{Z} &lt; 2.4$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

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: $\Delta \kappa_{Z} = \Delta g_{Z}^{Z} - \Delta \kappa_{Z} \tan^{2} \theta_{W}$ and $\lambda_{Z} = \lambda_{Z}$.
[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 WW$\gamma$ coupling limits and a search for non-standard-model WW + $WZ \rightarrow 4\nu$ jet jet production with limits on anomalous WW$\gamma$ and WWZ couplings.
[9] K. Hagiwara, S. Ishihara, R. Szałapski, and D. Zeppenfeld, Phys. Rev. D 48, 2182 (1993). They parameterize WWZ couplings in terms of the WW$\gamma$ couplings: $\Delta \kappa_{Z} = \Delta \kappa_{Z}(1 - \tan^{2} \theta_{W})/2$, $\Delta g_{Z}^{Z} = \Delta g_{Z}^{Z}/(2\cos^{2} \theta_{W})$ and $\lambda_{Z} = \lambda_{Z}$.
[15] We use a right-handed coordinate system with $\hat{z}$ pointing in the direction of the proton beam and $\hat{y}$ pointing upwards.