Measurement of the $WZ \to \ell\ell\ell\ell$ cross section and limits on anomalous triple gauge couplings in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a new measurement of the $W Z \to ℓ ν ℓ ℓ (ℓ = e, μ)$ cross section and limits on anomalous triple gauge couplings. Using 4.1 fb$^{-1}$ of integrated luminosity of $p \bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, we observe 34 $W Z$ candidate events with an estimated background of 6.0 ± 0.4 events. We measure the $W Z$ production cross section to be 3.90$^{+1.00}_{−0.90}$ pb, in good agreement with the standard model prediction. We find no evidence for anomalous $WWZ$ couplings and set 95% C.L. limits on the $κ$ parameter. The method we use is based on the $W$ and $Z$ boson production cross section measured with high precision, and the $W Z$ decay rate measured with high precision. The total number of events observed is 34, which is in good agreement with the standard model prediction of 34.0 ± 1.0 events. The six 95% C.L. limits on the $κ$ parameter are 0.027 < $κ < 0.080$, in the HISZ parameterization for a $Λ = 2$ TeV form factor scale. These are the best limits to date obtained from the direct measurement of the $W W Z$ vertex.

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The standard model (SM) of particle physics has been extensively tested in the past three decades and is found to be in excellent agreement with experimental observations. It is widely assumed, however, that the SM is only a low energy approximation of a more general theory. Therefore, any significant deviation from the SM predictions yields information on the nature of a more fundamental theory. Production of $W Z$ pairs is the least studied diboson process within the SM, as it is a charged boson pair. A detailed study of this process probes the electroweak sector of the SM. In addition, searches for new phenomena in the production of heavy gauge boson pairs are interesting, as many extensions of the SM predict additional heavy gauge bosons that can decay into a $W Z$ boson pair.
here and maintain unitarity at high energies. In the case of the \( t \)- and \( u \)-channels, the \( W \) and \( Z \) bosons are radiated from initial state quarks, while the \( s \)-channel production occurs via the \( WWZ \) triple gauge boson vertex, which is a consequence of the non-Abelian nature of the SM.

There are 14 free parameters describing the generalized Lagrangian for the \( WWV \) interaction $^{[3, 4]}$, where \( V \) is either a \( Z \) boson or a photon. Assuming gauge invariance and conservation of the \( C, \, P, \) and \( CP \) symmetries, only six remain. Their notation and SM values are \( \lambda_1 = 0 \), \( \kappa_V = g_I^V = 1 \) for the \( WWV \) vertex, while the deviations from the SM values are noted as \( \Delta \kappa_V \), \( \Delta g_I^V \) and \( \lambda_V \). The \( U(1) \) electromagnetic gauge invariance implies \( \Delta g_\gamma = 0 \).

In this Letter, we describe the \( WWZ \) vertex in three-dimensional (3D) phase space of coupling parameters, \( \Delta \kappa_Z \), \( \Delta g_I^Z \) and \( \lambda_Z \). We also consider the HISZ parameterization $^{[5]}$ that implies \( \Delta \kappa_Z = \Delta g_I^Z (\cos^2 \theta_W - \sin^2 \theta_W) \). Thus, the \( WWZ \) vertex can be described by \( \Delta \kappa_Z \) and \( \lambda_Z \) only.

If the coupling parameters have non-SM values, new physics is required to prevent gauge boson production from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies. The high energy behavior is controlled by introducing a dipole from violating unitarity at high energies.

The \( WZ \) production cross section was previously measured to be \( \sigma(p\bar{p} \rightarrow WZ) = 5.0^{+1.8}_{-1.6} \text{ pb} \)$ $^{[3]}$ and \( \sigma(p\bar{p} \rightarrow WZ) = 2.7^{+1.7}_{-1.3} \text{ pb} \)$ $^{[3]}$, by the CDF and D0 collaborations, respectively, using \( \sim 1 \) \( \text{fb}^{-1} \) of integrated luminosity. Combined limits on the gauge couplings from the CERN LEP collider were obtained $^{[10]}$ by the indirect measurement of the \( WWZ \) coupling in the \( e^+e^- \rightarrow W^+W^- \) process. The only direct measurement of \( WWZ \) couplings was performed at the Tevatron. Using \( 1 \text{ fb}^{-1} \) of integrated luminosity, 95\% C.L. limits on anomalous \( WWZ \) couplings were derived $^{[3]}$ by the D0 experiment: \( -0.17 < \lambda_Z < 0.21 \), \( -0.14 < \Delta g_I^Z < 0.34 \) for the HISZ relation and \( -0.12 < \Delta \kappa_Z = \Delta g_I^Z < 0.29 \), using \( \Lambda = 2 \text{ TeV} \). The CDF experiment used data equivalent to \( 350 \text{ pb}^{-1} \) of integrated luminosity that resulted in 95\% C.L. limits on anomalous \( WWZ \) couplings $^{[11]}$: \( -0.28 < \lambda_Z < 0.28 \) and \( -0.50 < \Delta \kappa_Z < 0.43 \) assuming equal coupling relation between \( WWZ \) and \( WW\gamma \) couplings and \( \Lambda = 1.5 \text{ TeV} \).

In this Letter, we present a new measurement of the \( WZ \) production cross section and set 95\% C.L. limits on the deviation from the SM predictions of triple gauge couplings \( (\lambda_Z, \Delta \kappa_Z, \Delta g_I^Z) \) using data equivalent to \( 4.1 \text{ fb}^{-1} \) of integrated luminosity of \( pp \) collisions at \( \sqrt{s} = 1.96 \text{ TeV} \) at the Tevatron collected by the D0 detector. This supersedes the previous D0 measurement. We consider only the leptonic decays of the \( W \) and \( Z \) bosons into final states with electrons, muons, and with missing transverse energy \( (E_T) \) $^{[12]}$ due to the neutrino from the \( W \) boson decay.

The detailed description of the D0 detector can be found elsewhere $^{[12]}$, while here we present a brief overview of the main sub-systems of the detector. The innermost part is a central tracking system surrounded by a 2 T superconducting solenoidal magnet. The two components of the central tracking system, a silicon microstrip tracker and a central fiber tracker, are used to reconstruct interaction vertexes and provide the measurement of the momentum of charged particles. The tracking system and a magnet are followed by the calorimetry system that consists of central (CC) and endcap (EC) electromagnetic and hadronic uranium-liquid argon sampling calorimeters, and an intercryostat detector (ICD).

A central calorimeter and two endcap calorimeters cover the pseudorapidity ranges \( |\eta| < 1.1 \) and \( 1.5 < |\eta| < 2.5 \) and CC electrons within \( |\eta| < 1.1 \). The cluster in the CC or EC must be isolated and have a shower shape consistent with that of an electron. In the intercryostat region (ICR), \( 1.1 < |\eta| < 1.5 \), we cluster energy found in the CC, ICD, or EC detectors. These ICR electrons are required to pass a neural network discriminant that uses the cluster’s shower shape and associated track information. A muon candidate is reconstructed as segments within the muon system that are matched to a track reconstructed in the central tracker. The muon candidate track must be isolated from activity in the tracker and the calorimeter.

The Monte Carlo (MC) samples of \( WZ \) signal and \( ZZ \) background are produced using the \textsc{pythia} $^{[13]}$ generator. The production of the \( W \) and \( Z \) bosons in association with jets (\( W+\text{jets}, \, Z+\text{jets} \)), collectively referred to as \( V+\text{jets} \), and \( t\bar{t} \) processes are generated using \textsc{alpgen} $^{[14]}$ interfaced with \textsc{pythia} for showering and hadronization. All MC samples are passed through the \textsc{geant} $^{[16]}$ simulation of the D0 detector. The simulated samples are further corrected to describe the luminosity dependence of the trigger and reconstruction efficiencies in data, as well as the beam spot position. All MC samples are normalized to the luminosity in data using next-to-leading order (NLO) calculations of the cross sections and are subject to the same selection criteria as that applied to data.

We consider four independent decay signatures: \( \text{e}e\text{e} + E_T, \, \text{e}e\mu + E_T, \, \mu\mu\mu + E_T, \) and \( \mu\mu\mu + E_T \). Electron reconstructed in the ICR must be selected as one of the electrons from the \( Z \) boson decay. We require the events to
have at least three lepton candidates with $p_T > 15$ GeV that originate from the same vertex and separated from each other by at least $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 0.5$. The event must also have a significant $E_T$ to account for the unobserved neutrino. We require $E_T$ to be above 20 GeV. Events are selected using triggers based on electrons and muons. Since there are multiple high $p_T$ leptons from the decay of the heavy gauge bosons the trigger efficiency is measured to be 98% $\pm$ 2% for all signatures.

In the $WZ$ candidate selection, we first identify the leptons from the $Z$ boson decay. We consider all pairs of electrons or muons, additionally requiring opposite electrical charge in the cases of muon pairs or electron pairs including an ICR electron. The pair that has an invariant mass closest to and consistent with the $Z$ boson nominal mass is selected as coming from the $Z$ boson decay. If such pair is not found the event is rejected. The lepton from the $W$ boson decay is selected as the one with the highest transverse momentum from the remaining unassigned muons and CC or EC electrons in the event. This assignment is studied in the simulation and found to be 100% correct for $ee\mu$ and $\mu\mu e$ channels. It is found to be correct in about 92% and 89% of cases for $eee$ and $\mu\mu\mu$ signatures, respectively. The effects of misassignment on the product of acceptance and efficiency of the selection criteria, $A \times \epsilon$, are estimated in the signal simulation. Values of $A \times \epsilon$ measured using the assignment method described above differ from those obtained using MC generator-level information by less than one per cent. Therefore, the systematic uncertainty on $A \times \epsilon$ due to the misassignment is neglected in this analysis.

In order to reduce the background contamination, the thresholds in the selection criteria are further optimized for each $WZ$ decay mode by maximizing $S/\sqrt{S+B}$. Here, $S$ is the expected number of $WZ$ signal events and $B$ is the total number of background events. The simulation is used to estimate $S$ as well as to measure $A \times \epsilon$ for each decay signature. The kinematic selection criteria are applied to measure the acceptance in simulations, while the lepton identification efficiencies are measured in data. The results are summarized in Table I.

The major background is from processes with a $Z$ boson and an additional object misidentified as the lepton from the $W$ boson decay. Such processes are $Z+jets$, $ZZ$, and $Z\gamma$. A small background contribution is expected from processes without $Z$ boson, such as $W+jets$ and $t\bar{t}$ processes.

The $ZZ$ and $t\bar{t}$ backgrounds are estimated from the simulation, while the $V$+jets, with $V$ being either a $Z$ or $W$ bosons, and $Z\gamma$ backgrounds are estimated using data-driven methods.

One or more jets in the $V$+jets process can be misidentified as a lepton from the $W$ or $Z$ boson decays. To estimate this contribution, we define a false lepton category for electrons and muons. A false electron is required to have most of its energy deposited in the electromagnetic calorimeter and satisfy electron calorimeter isolation criteria, while having a shower shape inconsistent with that of an electron. A muon candidate is categorized as false if it fails the isolation criteria. These requirements ensure that the false lepton is either a misidentified jet or a lepton from the semi-leptonic decay of heavy flavor quarks.

Using a multijet data sample, we measure the ratio of misidentified leptons passing two different selection criteria, false lepton and signal lepton, as a function of $p_T$ and $\eta$ for electrons and muons, respectively. We then select a sample of $Z$ boson decays with an additional false lepton candidate for each final state signature. The contribution from the $V$+jets background is estimated by scaling the number of events in this sample by the corresponding $p_T$- or $\eta$-dependent misidentification ratio.

Initial or final state radiation in $Z\gamma$ events can mimic the signal process if the photon either converts into $e^+e^-$ pair or when a central track is wrongly matched to a photon. As a result, the $Z\gamma$ process is a background to two out of the four final state signatures with $W \rightarrow e\nu$ decays. To estimate the contribution from this background, we measure the rate at which a photon is misidentified as an electron. This is estimated using a data sample of $Z \rightarrow \mu\mu$ events with a final state radiation photon, since it offers an almost background-free source of photons due to the invariant mass, $M(\mu\mu\gamma)$, constraint to the $Z$ boson mass. The muon decay of the $Z$ boson is chosen to avoid an ambiguity when assigning the electromagnetic shower to the final state photon candidate. The misidentification rate is measured as a function of the $p_T$ of the electromagnetic shower. The $Z\gamma$ contribution is estimated by multiplying the $p_T$-dependent misidentification rate by the photon $p_T$ distribution in the $Z\gamma$ NLO MC simulation.

The selection yields 34 $WZ$ candidate events with an estimated $23.3 \pm 1.5$ signal, and $6.0 \pm 0.6$ background events. The number of observed candidate events as well as the expected numbers of signal and background events for each signature are summarized in Table I. The distribution of the invariant mass of the $Z$ boson candidates is given in Fig. I. The transverse mass of the $W$ boson candidate is calculated as $M_T^2 = M_T^2 + M_T^2$, where $M_T$ is the transverse mass defined in the $Z$ boson decay plane.
A systematic uncertainty of 5% is assigned on the lepton identification efficiencies are 5%, 4%, and 6% for CC/EC electrons, muons, and ICR electrons, respectively. The systematic uncertainties on the lepton identification efficiencies are 5%, 4%, and 6% for CC/EC electrons, muons, and ICR electrons, respectively. The systematic uncertainty assigned to the PDF choice is 5%.

Events/10 GeV

FIG. 1: (Color online) Invariant mass distribution of selected Z candidates in data (black points), with WZ signal (open histogram) and total background (dark histogram) overlaid.

Events/10 GeV

FIG. 2: (Color online) Transverse mass distribution of selected W candidates in data (black points), with WZ signal (open histogram) and total background (dark histogram) overlaid.

Events/30 GeV

FIG. 3: (Color online) The Z boson $p_T$ spectrum from data (points), total background (dark histogram), the SM WZ single + total background (open histogram), and two anomalous coupling models (dashed and dotted histograms). The last bin includes overflows.

A three-dimensional grid of values of anomalous couplings $\Delta\kappa_{Z}, \Delta\eta_{1}^{Z},$ and $\lambda_{Z}$ is produced. For each point of the grid we generate $WZ$ production using MCFM.
and obtain normalized to luminosity $p_T$ spectrum of the $Z$ boson. This spectrum combined with that from the estimated background is compared with the measured $Z$ boson $p_T$ spectrum in data. The likelihood of the match is calculated with the assumption of Poisson statistics for the signal and Gaussian uncertainties for the background. The two-dimensional 95% C.L. limit contours in three planes, $(\Delta \kappa_Z, \lambda_Z)$, $(\Delta g^Z_1, \lambda_Z)$, and $(\Delta g^Z_1, \Delta \kappa_Z)$, are shown in Fig. 4. In each case the third coupling is restricted to the SM value. For the HISZ parameterization the results are presented as limits on two coupling parameters: $\Delta \kappa_Z$ and $\lambda_Z$. The corresponding two-dimensional 95% C.L. limit contour is shown on Fig. 5. The one-dimensional limits on the coupling parameters obtained without any coupling relation and with HISZ parameterization are summarized in Table III.

| Coupling relation | 95% C.L. Limit |
|-------------------|---------------|
| $\Delta g^Z_1 = \Delta \kappa_Z = 0$ | $-0.075 < \lambda_Z < 0.093$ |
| $\lambda_Z = \Delta \kappa_Z = 0$ | $-0.053 < \Delta g^Z_1 < 0.156$ |
| $\lambda_Z = \Delta g^Z_1 = 0$ | $-0.376 < \Delta \kappa_Z < 0.686$ |
| $\Delta \kappa_Z = 0$ (HISZ) | $-0.075 < \lambda_Z < 0.093$ |
| $\lambda_Z = 0$ (HISZ) | $-0.027 < \Delta \kappa_Z < 0.080$ |

Table III: One-dimensional 95% C.L. limits on anomalous coupling parameters obtained from varying one of the couplings while fixing the remaining couplings to the SM values (top three results). The last two results correspond to one-dimensional 95% C.L. limits on anomalous coupling parameters for the HISZ parameterization. A form factor scale of $\Lambda = 2$ TeV is used.

In summary, we have presented a measurement of the $WZ$ production cross section using 4.1 fb$^{-1}$ of integrated luminosity of D0 data. We observe 34 events with $23.3 \pm 1.5$ expected signal events and $6.0 \pm 0.6$ estimated background events. We measure the $WZ$ cross section to be $3.96^{+1.06}_{-0.90}$ pb, which is in agreement with the SM NLO prediction of $3.25 \pm 0.19$ pb$^{[11]}$. This is the most precise measurement to date of the $WZ$ cross section. We find no evidence for anomalous $WWZ$ couplings and set 95% C.L. limits of $-0.075 < \lambda_Z < 0.093$.

\[\begin{array}{cccc}
\text{Source} & eee & ee\mu & e\mu\mu & \mu\mu\mu \\
\hline
ZZ & 0.39 \pm 0.07 & 1.48 \pm 0.20 & 0.40 \pm 0.07 & 1.26 \pm 0.23 \\
V+jets & 0.63 \pm 0.17 & 0.56 \pm 0.24 & 0.03 \pm 0.01 & 0.17 \pm 0.05 \\
Z\gamma & 0.28 \pm 0.08 & < 0.001 & 0.66 \pm 0.34 & < 0.001 \\
tt & 0.03 \pm 0.01 & 0.05 \pm 0.01 & 0.04 \pm 0.01 & 0.03 \pm 0.01 \\
\hline
\text{Total bkg.} & 1.33 \pm 0.21 & 2.11 \pm 0.31 & 1.13 \pm 0.35 & 1.46 \pm 0.24 \\
WZ signal & 5.9 \pm 0.8 & 6.9 \pm 0.8 & 4.7 \pm 0.6 & 5.8 \pm 0.8 \\
\text{Observed} & 9 & 11 & 9 & 5 \\
\end{array}\]

Table II: Number of observed events, expected number of signal events, and expected number of background events for each final state signature with total (statistical and systematic) uncertainties.

FIG. 4: (Color online) Two-dimensional 95% C.L limit contours on $(\Delta \kappa_Z, \lambda_Z)$ (a), $(\Delta g^Z_1, \lambda_Z)$ (b), and $(\Delta g^Z_1, \Delta \kappa_Z)$ (c). The point corresponds to the minimum of the likelihood surface. The vertical and horizontal lines represent the one-dimensional limits calculated separately. A form factor scale of 2 TeV is used.
and $-0.027 < \Delta \kappa_Z < 0.080$ for the HISZ parametrization using $\Lambda = 2$ TeV. These are the most stringent limits on $WWZ$ couplings obtained from the study of direct $WZ$ production.

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