Measurement of the $p\bar{p} \rightarrow WZ + X$ cross section at $\sqrt{s} = 1.96$ TeV and limits on $WWZ$ trilinear gauge couplings

V. M. Abazov
Joint Institute for Nuclear Research, Dubna, Russia

Kenneth A. Bloom
University of Nebraska-Lincoln, kbloom2@unl.edu

Gregory R. Snow
University of Nebraska-Lincoln, gsnow1@unl.edu

D0 Collaboration

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The $SU(2)_{L} \times U(1)_{Y}$ structure of the standard model (SM) Lagrangian requires that the massive electroweak gauge bosons, the $W$ and $Z$ bosons, interact with one another at trilinear and quadrilinear vertices. In the SM, the production cross section for $p \bar{p} \rightarrow WZ + X$, $\sigma(WZ)$, depends on the strength of the $WZ$ coupling, $s_{WZ} = -e \cot \theta_{W}$, where $e$ is the positron charge and $\theta_{W}$ is the weak mixing angle. At $\sqrt{s} = 1.96$ TeV, the SM predicts $\sigma_{WZ} = 3.68 \pm 0.25$ pb [1]. Any significant deviation from this prediction would be evidence for new physics.

The $WZ$ interaction can be parametrized by a generalized effective Lagrangian [2,3] with CP-conserving trilinear gauge coupling parameters (TGCs) $g^{T}$, $\kappa_{Z}$, and $\lambda_{Z}$ that describe the coupling strengths of the vector bosons to the weak field. The TGCs are commonly presented as deviations from their SM values, i.e. as $\Delta g^{T} = g^{T} - 1$, $\Delta \kappa_{Z} = \kappa_{Z} - 1$, and $\Delta \lambda_{Z}$, where $\lambda_{Z} = 0$ in the SM. Since tree-level unitarity restricts the anomalous couplings to their SM values at asymptotically high energies, each of the couplings must be parametrized as a form factor, e.g. $\lambda_{Z}(\hat{s}) = \lambda_{Z}/(1 + \hat{s}/\Lambda^{2})^{2}$, where $\Lambda$ is the form factor scale and $\hat{s}$ is the square of the invariant mass of the $WZ$ system. New physics will result in anomalous TGCs and an enhancement in the production cross section as well as modifications to the shapes of kinematic distributions, such as the $W$ and $Z$ bosons transverse momenta. Because the Fermilab Tevatron is the only particle accelerator that can provide the charged state $WZ + X$, this measurement provides a unique opportunity to study the $WZ$ TGCs without any assumption on the values of the $WW\gamma$ couplings. Measurements of TGCs using the $WW$ final state [4–8] are sensitive to both the $WW\gamma$ and $WZ$ couplings at the same time and must make some assumption as to how they are related to each other.

$WZ$ production measurements and studies of $WWZ$ couplings have been presented previously. The D0 Collaboration measured $\sigma_{WZ} = 4.5^{+3.8}_{-2.6}$ fb, with a 95% C.L. upper limit of 13.3 pb, using 0.3 fb$^{-1}$ of $p \bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [9]. The observed number of candidates was used to derive the most restrictive available limits on anomalous $WWZ$ couplings. More recently, the CDF Collaboration measured $\sigma_{WZ} = 5.0^{+1.9}_{-1.5}$ pb using 1.1 fb$^{-1}$ of $p \bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [10], but did not present any results on $WWZ$ couplings.

We present measurements of the process $p \bar{p} \rightarrow WZ + X \rightarrow \ell^{-} \nu_{\ell} \ell^{-} \nu_{\ell}$ at $\sqrt{s} = 1.96$ TeV, where $\ell$ and $\ell'$ are electrons or muons. Using 1 fb$^{-1}$ of data from the D0 experiment, we observe 13 candidates with an expected background of $4.5 \pm 0.6$ events and measure a cross section $\sigma(WZ) = 2.7^{+1.3}_{-1.1}$ pb. From the number of observed events and the $Z$ boson transverse momentum distribution, we limit the trilinear $WWZ$ gauge couplings to $-0.17 \leq \lambda_{Z} \leq 0.21(\Delta \kappa_{Z} = 0)$ at the 95% C.L. for a form factor scale $\Lambda = 2$ TeV. Further, assuming that $\Delta g^{T} = \Delta \kappa_{Z}$, we find $-0.12 \leq \Delta \kappa_{Z} \leq 0.29(\lambda_{Z} = 0)$ at the 95% C.L. These are the most restrictive limits on the $WWZ$ couplings available to date.
or three muons, the trigger efficiencies are estimated to be electrons is estimated to be.

Events collected from 2002–2006 using single muon, single electron, di-electron, and jet triggers were used for signal and background studies. The integrated luminosities [17] for the $e+e-$, $ee\mu$, $\mu\mu\mu$, and $\mu\mu\mu$ final states are 1070 pb$^{-1}$, 1020 pb$^{-1}$, 944 pb$^{-1}$, and 944 pb$^{-1}$, respectively. There is a common 6.1% systematic uncertainty on the integrated luminosities.

The $WZ$ event selection requires three reconstructed, well-isolated leptons with $p_T > 15$ GeV/$c$. All three leptons must be associated with isolated tracks that originate from the same collision point and must satisfy the electron or muon identification criteria outlined above. To select $Z$ bosons, and further suppress background, the invariant mass of a like-flavor lepton pair must fall within the range 71 to 111 GeV/$c^2$ for $Z \rightarrow ee$ events, and 50 to 130 GeV/$c^2$ for $Z \rightarrow \mu\mu$ events, with the mass ranges set by the mass resolution. For $ee$ and $\mu\mu\mu$ decay channels, the lepton pair with invariant mass closest to that of the $Z$ boson mass are chosen to define the $Z$ boson daughter particles. The $E_T$ is required to be greater than 20 GeV, consistent with the decay of a $W$ boson. The transverse recoil of the WZ system, calculated using the vector sum of the transverse momenta of the charged leptons and missing transverse energy, is required to be less than 50 GeV/$c$. This selection reduces the background contribution from $t\bar{t}$ production to a negligible level.

$WZ$ event detection efficiencies are determined for each of the four final states. Monte Carlo (MC) events are generated using PYTHIA [18] and a GEANT [19] detector simulation and then processed using the same reconstruction chain as the data. The efficiency determinations.

A total of 13 $WZ$ candidate events is found. Figure 1 shows $E_T$ versus the dilepton invariant mass for the background, the expected $WZ$ signal, and the data, including the candidates. Table I also details the number of candidates in each channel.

The main background for $WZ \rightarrow \ell\nu\ell\bar{\ell}$ are $Z+X$ events where $X$ is a jet that has been misidentified as an electron or muon. We assess the background from $Z+\text{jets}$ production by using an inclusive jet data sample that is selected with an independent jet trigger. Events characteristic of QCD two-jet production are used to measure the probability, as a function of jet $E_T$ and $\eta$, that a single jet

TABLE I. The numbers of candidate events, expected signal events, and estimated background events, and the overall detection efficiency for the four final states.

| Final state | Number of candidate events | Expected signal events | Estimated background events | Overall efficiency |
|-------------|---------------------------|------------------------|-----------------------------|-------------------|
| $eee$       | 2                         | $2.3 \pm 0.2$          | $1.2 \pm 0.1$               | $0.16 \pm 0.02$   |
| $ee\mu$     | 1                         | $2.2 \pm 0.2$          | $0.46 \pm 0.03$             | $0.17 \pm 0.02$   |
| $\mu\mu\nu$| 8                         | $2.2 \pm 0.3$          | $2.0 \pm 0.4$               | $0.17 \pm 0.03$   |
| $\mu\mu\mu$| 2                         | $2.5 \pm 0.4$          | $0.86 \pm 0.06$             | $0.21 \pm 0.03$   |
| Total       | 13                        | $9.2 \pm 1.0$          | $4.5 \pm 0.6$               | —                 |
will be misidentified as a muon or electron. Next, subsamples of $ee + \text{jets}$, $e\mu + \text{jets}$, and $\mu\mu + \text{jets}$ events are selected using the same criteria as for the WZ signal except that the requirements for a third lepton in the event are dropped. The single jet-lepton misidentification probabilities are then convoluted with the measured jet distributions in the dilepton $+\text{jets}$ subsamples to provide an estimate of the background from $Z +\text{jets}$ events. The contribution for all four decay modes totals $1.3 \pm 0.1$ events.

All other backgrounds are determined using MC. Non-negligible backgrounds include SM ZZ production, $Z\gamma$ production, and $W^+Z$, $WZ^*$, or $W\gamma^*$ production. We define these processes as three-lepton final states produced through the decay of one on-mass-shell and one off-shell vector boson. These backgrounds and their determination are described in the following paragraphs.

$ZZ$ production becomes a background when both $Z$ bosons decay to charged leptons and one of the final state leptons escapes detection, thus mimicking a neutrino. The total contribution from $ZZ$ production is $0.70 \pm 0.08$ events.

$Z\gamma$ final states can be misidentified as $WZ$ events if the photon is misreconstructed as an electron and there is sufficient $E_T$. We estimate the $\ell\ell + \gamma$ contribution using $Z +\gamma$ MC [20] combined with the probability for a photon to be misidentified as an electron ($4.2 \pm 1.5\%$) determined from studies of events with photons. This process is a background only to the $eee$ and $\mu\mu e$ final states. The total contribution is $1.4 \pm 0.5$ events.

The contribution to the background from off-shell bosons should be nearly the same as occurs in similar processes and a fraction relative to the expected signal is determined from $ZZ$ MC events generated using PYTHIA. It depends on the decay channel and varies from 8% for the $ee\mu$ mode to 15% for the $\mu\mu\mu$ mode. The uncertainties include all of those used for the signal plus an additional 16% systematic component to account for uncertainties in the off-shell component of the MC. The total contribution of this background is $0.99 \pm 0.19$ events.

To cross check the background estimates, we compare the number of observed events with that expected when we do not apply the dilepton invariant mass selection and the $E_T$ selection. We expected to observe $12.5 \pm 1.4$ events from signal and $62.9 \pm 8.4$ events from backgrounds. We observe the 78 events shown in Fig. 1.

The SM predicts that $9.2 \pm 1.0$ WZ events are expected to be observed in the data sample. The probability for the background, $4.5 \pm 0.6$ events, to fluctuate to 13 or more events is $1.2 \times 10^{-3}$, which translates to a one-sided Gaussian significance of 3.0$\sigma$, determined by using a Poisson distribution for the number of observed events in each channel convoluted with a Gaussian to model the systematic uncertainty on the background. A likelihood method [21] taking into account correlations among systematic uncertainties is used to determine the most probable WZ cross section. The cross section $\sigma(WZ)$ is $2.7^{+1.7}_{-1.1}$ pb, where the $\pm 1\sigma$ uncertainties are the 68% C.L. limits from the minimum of the negative log likelihood. The uncertainty is dominated by the statistics of the number of observed events.

By comparing the measured cross section and $p_T^Z$ distribution to models with anomalous TGCs, we set one- and two-dimensional limits on the three $CP$-conserving couplings. A comparison of the observed $Z$ boson $p_T$ distribution with MC predictions is shown in Fig. 2. We use the Hagiwara-Woodside-Zeppenfeld (HWZ) [22] leading-order event generator processed with a fast detector and event reconstruction simulation to produce events with anomalous WWZ couplings and simulate their efficiencies and acceptances. The HWZ event generator does not account for $\tau$ final states, and as a result, we treat the 0.7 event $\tau$ contribution as background for the WWZ coupling limit setting procedure. The method used to determine the coupling limits is described in Ref. [23]. Limits are set on the coupling parameters $\Lambda_{Z}$, $\Delta g_{7}^{Z}$, and $\Delta Z_{\tau}$ for two sets of form factor scale, $\Lambda$.

| $\Lambda$ | $1.5$ TeV | $2.0$ TeV |
|-----------|-----------|-----------|
| $-0.18 < \Lambda_{Z} < 0.22$ | $-0.17 < \Lambda_{Z} < 0.21$ | $-0.12 < \Delta Z_{\tau} = \Delta g_{7}^{Z} < 0.29$ |
| $-0.15 < \Delta g_{7}^{Z} < 0.35$ | $-0.14 < \Delta g_{7}^{Z} < 0.34$ | $-0.14 < \Delta g_{7}^{Z} < 0.31$ |
| $-0.14 < \Delta Z_{\tau} = \Delta g_{7}^{Z} < 0.31$ | $-0.12 < \Delta Z_{\tau} = \Delta g_{7}^{Z} < 0.29$ | $-0.14 < \Delta Z_{\tau} = \Delta g_{7}^{Z} < 0.31$ |

FIG. 2. The reconstructed $Z$ boson $p_T$ of the WZ candidate events used in the WWZ coupling parameter limit setting procedure. The solid histogram is the expected sum of signal and background for the case of the WWZ coupling parameters set to their SM values. The dotted and double dotted histograms are the expected sums of signal and background for two different cases of anomalous WWZ coupling parameter values. The black dots are the data. The final bin is the overflow bin.

TABLE II. One-dimensional 95% C.L. intervals on $\Lambda_{Z}$, $\Delta g_{7}^{Z}$, and $\Delta Z_{\tau}$ for two sets of form factor scale, $\Lambda$. 

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The form factor scale, $\Lambda$ [24], associated with each grid, is chosen such that the limits are within the unitarity bound.

In summary, we present the results of a search for $WZ$ production in 1.0 fb$^{-1}$ of $p \bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We observe 13 trilepton candidate events with an expected 9.2 $\pm$ 1.0 signal events and 4.5 $\pm$ 0.6 events from background. This gives an observed significance of 3.0$\sigma$. We measure the $WZ$ production cross section to be $2.7^{+1.1}_{-0.9}$ pb, in agreement with the SM prediction. We use the measured cross section and $p_T^Z$ distribution to improve constraints on $WZ$ trilinear gauge couplings by a factor of 2 over the previous best results.

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$$\Delta \kappa_Z = \Delta \alpha (1 - \tan^2 \theta_W)/2, \quad \Delta g_1^Z = \Delta \alpha / (2 \cos^2 \theta_W)$$

and $\lambda_Z = \lambda_Y$.

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$$\Delta \kappa_Z = \Delta g_1^Z = \Delta \alpha, \tan^2 \theta_W$$

and $\lambda_Z = \lambda_Y$.

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