DØnote 4569-CONF

# Search at DØ for Inclusive $WZ$ Diboson Events in Trilepton Final States at $\sqrt{s} = 1.96$ TeV

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*URL http://www-d0.fnal.gov*
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Presented is a preliminary search for $WZ$ diboson events in trilepton final states using data on $p\bar{p}$ collision collected by the DØ experiment during 2002–2003 at the Fermilab Tevatron at a center-of-mass energy of 1.96 TeV. The cleanest experimental signal for the $WZ$ events is from a pair of leptons ($e^+e^-$ or $\mu^+\mu^-$) from the decay of the Z boson, and another lepton ($e$ or $\mu$) with large transverse momentum ($p_T$) and a large imbalance $p_T$ in the event (missing neutrino) from the leptonic decay of the W boson. One trilepton event with the $WZ$ decay characteristics is observed in DØ data. With an estimated background of $0.39 \pm 0.02$ events and integrated luminosities ranging from 138.2 – 170.5 pb$^{-1}$ for different trilepton final states, we set a 95% confidence level upper limit for the $WZ$ production cross section of 15.1 pb.

*Preliminary Results for Summer 2004 Conferences*

## I. INTRODUCTION

The electroweak component of the standard model (SM) is based on the non-Abelian gauge group $SU(2)_L \times U(1)_Y$ symmetry transformations, and predicts that the electroweak gauge bosons ($W$ and $Z$) can interact directly through trilinear and quartic gauge-boson vertices. One of the important tests of the SM is the measurement of such couplings from $WZ$ production in $p\bar{p}$ collisions. This provides a sensitive probe of any low energy remnants of new physics operating at a higher scale, and is therefore complimentary to direct searches of new physics beyond the SM. The $WZ$ production cross section in the standard model depends on the $ZWW$ gauge coupling, shown in the Feynman diagrams for $WZ$ production in $p\bar{p}$ collisions.

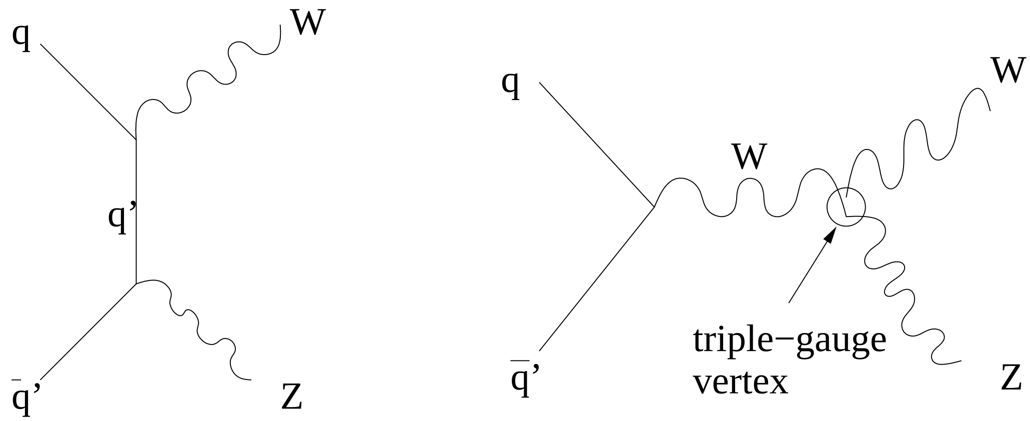


FIG. 1: Lowest-order Feynman diagrams for $WZ$ production in $p\bar{p}$ collisions, with the triple-gauge $ZWW$ vertex being of particular interest.

In Run I of the Fermilab Tevatron program, the DØ experiment searched for $WZ$ events, and set an upper limit for the $WZ$ cross section of 47 pb [1], compared to the SM prediction of 2.6 pb at $\sqrt{s}$=1.8 TeV. With a higher center-of-mass energy, more luminosity from the upgraded Tevatron, and an improved DØ detector, far more data is expected in the Run II. This has opened a new window of opportunity for the studies of $WZ$ diboson production. The predicted cross section for $WZ$ production at $\sqrt{s}$=1.96 TeV is 3.7±0.1 pb [2], which is based on next-to-leading-order(NLO) calculations using the latest parton distribution functions (PDF) of CTEQ6_M [3] and MRST2002 [4]. This is a 40% higher than the prediction for Run I.

The cleanest $WZ$ signals arise from trilepton final states from the the leptonic decay channels of the $Z$ and the $W$ bosons. However, the leptonic decay channels have very low branching ratios, which correspond to only about 0.35% for any given lepton family, and 1.5% for two families of leptons. The trilepton final states include $eee$, $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$, and an associated neutrino, which is reflected in an imbalance in transverse momentum in the final state (or missing transverse energy, $\not\!\!E_T$, in the DØ detector).

## II. APPARATUS OF THE DØ EXPERIMENT

The DØ detector is comprised of several sub-detectors, trigger and data acquisition systems [5]. A magnetic central-tracking system, which consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), is located within a 2 T superconducting solenoid magnet [6]. The SMT has $\approx 800,000$ individual strips with excellent coverage up to pseudorapidity $|\eta| < 3$. The CFT has eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers of 0.835 mm diameter, one doublet being parallel to the collision axis, and the other alternating by $\pm 3^\circ$ relative to the axis. Light signals are transferred via clear light fibers to solid-state photon counters (VLPC) that have $\approx 80$ % quantum efficiency.

Central and forward preshower detectors located just outside of the superconducting coil (in front of the calorimetry) are constructed of several layers of extruded triangular scintillator strips that are read out using wavelength-shifting fibers and VLPCs. The detectors outside the preshower are three liquid-argon/uranium calorimeters: a central section (CC) covering $|\eta|$ up to $\approx 1$, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$, each housed in a separate cryostat [5]. In addition to the preshower detectors, scintillators between the CC and EC cryostats provide sampling of developing showers at $1.1 < |\eta| < 1.4$.

A muon system resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two more similar layers after the toroids. Tracking at $|\eta| < 1$ relies on 10 cm wide drift tubes [5], while 1 cm mini-drift tubes are used at $1 < |\eta| < 2$.

Luminosity is measured using plastic scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The trigger and data acquisition systems are designed to accommodate the high luminosities of the upgraded Fermilab Tevatron in Run II. Based on preliminary information from tracking, calorimetry, and muon systems, the output of the first level of the trigger is used to limit the rate for accepted events to $\approx 1.5$ kHz. With more refined information at the second level, the rate is reduced further down to $\approx 800$ Hz. These first two levels of triggering rely mainly on hardware and firmware. The third and final level of the trigger, with access to all the event information, uses software algorithms and a computing farm, and reduces the output rate to $\approx 50$ Hz, which is written to tape.

## III. DATA ANALYSIS

### A. Data Sample

This analysis uses data collected at DØ during 2002–2003 and is based on dilepton ($ee$, $\mu\mu$ and $e\mu$) and dijet events reconstructed using DØ reconstruction program.

We select events from runs flagged as being of good quality, with all sub-detector systems, including the calorimeter, the muon, the CFT, and the SMT systems, operating reliably. Events with luminosity blocks that cannot be normalized are removed. Based on detailed selection criteria, integrated luminosities for different lepton final states are in this analysis correspond to 170.5 pb$^{-1}$ for the $eee$ final state, 144.9 pb$^{-1}$ for the $ee\mu$, 138.2 pb$^{-1}$ for the $\mu\mu e$ final state, and 142.2 pb$^{-1}$ for the $\mu\mu\mu$ final state.

Because there are three high-$p_T$ leptons in the final states, any lepton in the event can fire the DØ trigger system. From different studies, we determined the overall trigger efficiency for trilepton final states be close to 100% with the uncertainty less than 1%.

### B. Event Selection

The characteristic feature of $WZ$ leptonic-decays events is the presence of three high-$p_T$ leptons and large $\not\!\!E_T$. We first describe electron and muon identification criteria, and then present the details of $WZ$ event selection.

#### 1. *Electron Identification*

Electrons are identified by the distinctive pattern of energy deposition of electromagnetic showers in the calorimeter and by the presence of a track in the central tracker, that extrapolates from the interaction vertex to a cluster of hits in the calorimeter. The fiducial requirement is $|\eta| < 1.1$ for electrons from CC and $1.5 < |\eta| < 2.5$ for electrons from EC. The transverse momentum of an electron has to be $> 15.0$ GeV.

An acceptable electron must have an electromagnetic-energy (EM) fraction, $f_{\mathrm{EM}} > 0.9$, where $f_{\mathrm{EM}}$ is a ratio of energy found in the EM cells of the calorimeter to the total energy of a shower. Electron showers are usually compact and contained in the core EM cells. The isolation $\mathcal{I}$ is defined as the ratio of difference between total energy within a cone $R = 0.4(E_{tot})$ and EM energy within a cone $R = 0.2$ ($E_{\mathrm{EM}}$), relative to the energy in the EM core of the shower within a cone $R = 0.2$, $\mathcal{I} = \frac{E_{tot}(0.4) - E_{EM}(0.2)}{E_{EM}(0.2)}$, where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, and $\phi$ is the azimuthal angle. For an isolated electron, $\mathcal{I}$ is required to be $< 0.15$. A covariance matrix based on 7 variables for the shower in CC and 8 variables for shower in EC is used to compute a $\chi^2$ variable that represents the consistency of a cluster corresponding to that of an electron shower. The selection on this $\chi^2$ retains $\approx 95\%$ of all true electrons.

A good electron shower is also expected to have a well-matched track in the central tracking system with the ratio of calorimeter/momentum ($E/p_T$) measurements within the expectation for electron objects.

#### 2. *Muon Identification*

Muons are reconstructed using information from the muon, scintillation, central tracking, and calorimeter detectors. Muons from $W$ and $Z$ boson decays are usually isolated, have large transverse momentum, and have tracks in the outer muon spectrometer. A muon reconstructed in the toroid system is required to have $p_T > 15$ GeV and a matching track in the central tracker. The muon isolation selection requires the transverse energies of the calorimeter cells in an annular ring $0.1 < R < 0.4$ around each muon direction to be $\sum_{\text{cells},i} E_T^i < 2.5$ GeV. In addition, the sum of the transverse momenta of all tracks, other than that of the muon, in a cone of $R = 0.5$ around the muon track is required to be $< 3.5$ GeV.

### *3. Event Selection*

The $WZ$ diboson event selection requires three reconstructed leptons that pass the electron or muon identification criteria outlined in previous sections, and all must originate from the same interaction vertex. To avoid confusion between tracks, the separation between any pair of leptons is required to be $R > 0.2$. Figures 2(a-b) show the distributions of the like-flavor dilepton mass vs the missing transverse energy $\not\!\!E_T$for the inclusive dilepton events observed in the data. Also showns are those expected from $WZ$ events. The data is dominated by Drell-Yan and Z events with little $\not\!\!E_T$. A requirement of $\not\!\!E_T > 20$ GeV removes most of the background. To select $Z$ bosons and reduce background, the invariant mass of a like lepton pair has to be within the mass window of 71 GeV to 111 GeV for $Z \to ee$ events, and 51 GeV to 131 GeV for $Z \to \mu\mu$ events. These mass windows are set by the respective mass resolutions. For $eee$ and $\mu\mu\mu$ decay channels, the pair of leptons that has an invariant mass closest to the $Z$ mass is regarded as the source of leptons from a $Z$ boson. The third lepton is thus assumed to originate from a $W$ boson. To reject background from $t\bar{t}$ events, the vector sum of the transverse energies in all calorimeter cells, excluding the leptons ($T_{\text{had}}$) has to be $T_{\text{had}} < 50$ GeV.

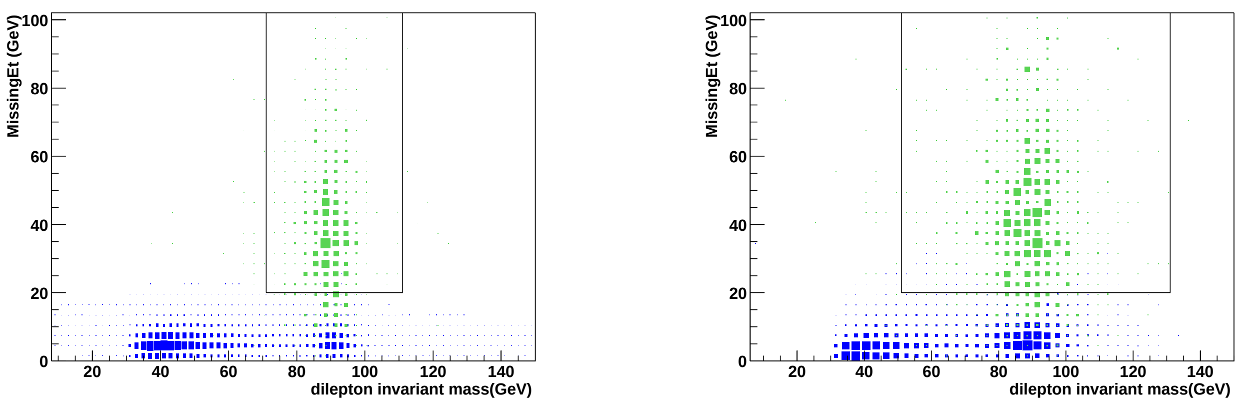


FIG. 2: Like-flavor dilepton invariant mass vs $\not\!\!E_T$distribution expected form WZ events (green) compared with that of inclusive dilepton events observed in the data (blue) for electrons (a) and muons (b). The lines indicate the selection cuts. For $eee$ and $\mu\mu\mu$ events, the pair with its mass closest to the $Z$ mass is plotted. The normalization is arbitary.

The above event selections are optimized by varying the acceptance and identification criteria and calculating the significance of the measurement, which is defined by $N_s/\sqrt{N_b}$, where $N_s$ is the number of signal and $N_b$ the number of estimated background events. The expected $N_s$ is calculated using SM predicted $WZ$ cross section, and $N_b$ is estimated background that depends on selection criteria. The selections that maximize the significance are used to define the event sample.

Applying all selection requirements leaves only one candidate $\mu\mu\mu$ event. The information for the event is summarized in Table I, and the event is displayed is in Fig. 3.

| $\ell_1$ | | | | $\ell_2$ | | | | $\ell_3$ | | | | $\vec{\not\!\!E}_T$ | | $m_{\ell_1\ell_2}$ | $m_T$ | $T_{had}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_x$ | $p_y$ | $p_z$ | $E$ | $p_x$ | $p_y$ | $p_z$ | $E$ | $p_x$ | $p_y$ | $p_z$ | $E$ | $\not\!\!E_T$ | $\phi$ | | | |
| 57.5 | 12.5 | 23.1 | 63.2 | -43.0 | -2.97 | 39.0 | 58.1 | 22.9 | 17.5 | -52.5 | 59.9 | 41.8 | 3.818 | 83.3 | 69.4 | 4.8 |

TABLE I: Summary of the measured values of the $WZ$ diboson candidate in the $\mu\mu\mu$ final state. The units for $p_i$(i=x,y,z), E, $m_{\ell\ell}$, $m_T$ and $T_{\text{had}}$ are in GeV, where the $m_{\ell\ell}$ is the invariant mass of the two muons, $\not\!\!E_T$ is missing transverse energy and $m_T$ is the transverse mass of $W \to \mu\nu$. The transverse mass is defined as $m_T = \sqrt{2E_T^\mu E_T^\nu[1 - \cos(\phi^\mu - \phi^\nu)]}$, where $E_T^\mu$ and $E_T^\nu$ are the transverse energies, and $\phi^\mu$ and $\phi^\nu$ are the azimuthal angles, of the muon and neutrino, respectively.

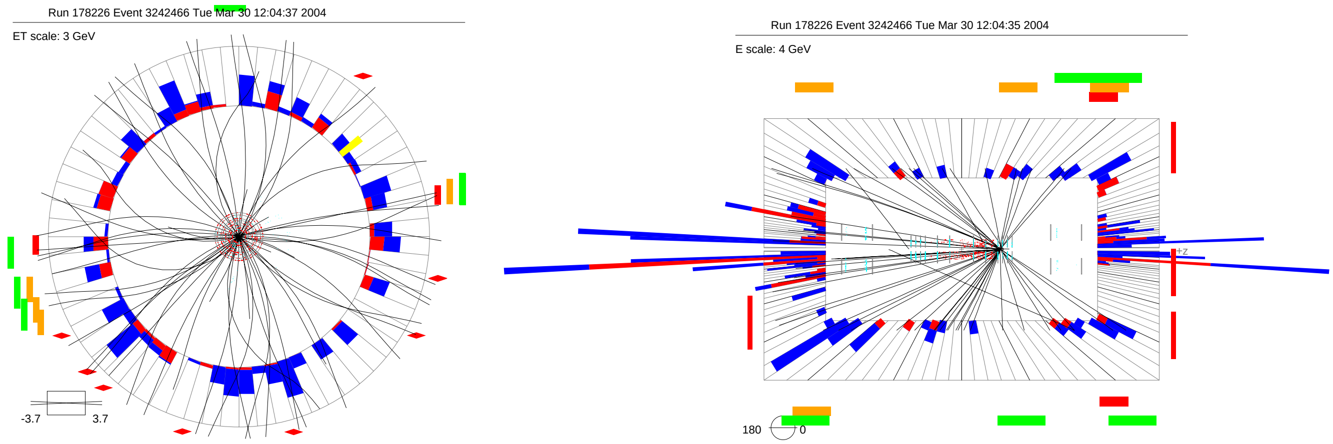


FIG. 3: The $WZ$ candidate event in $\mu\mu\mu$ channel. The $(\eta, \phi)$ values of the three muons are (0.38,0.21), (0.81,3.21) and (-1.36,0.65) respectively.

### C. Acceptance and Efficiency

The acceptance for inclusive $WZ$ events includes the geometric and kinematic cutoffs. The acceptance is calculated using Monte Carlo samples generated with the PYTHIA generator and simulated with the GEANT-based DØ detector-simulation program. The acceptances are calculated by counting the number of events that pass all selection criteria, except the lepton identification and the track-matching requirements. The overall acceptances are $0.283 \pm 0.008$, $0.279 \pm 0.008$, $0.287 \pm 0.009$ and $0.294 \pm 0.008$ for $eee$, $ee\mu$, $\mu\mu e$ and $\mu\mu\mu$ final states, respectively.

Lepton-identification and track-matching efficiencies are estimated using $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events. One of the leptons from the $Z$ is required to pass all the lepton selections, and the other lepton is used as an unbiased sample for estimating efficiency. The $Z \to \ell^+\ell^-$ invariant mass is then fitted with a Breit-Wigner function convoluted with a Gaussian function, and an exponential decay function to describe the background.. The area under the fitting function, ignoring the exponential function and any interference effects, is defined as the $Z$ signal. The efficiency is then determined from the unbiased lepton sample, by comparing signal/background ratios before and after applying the selections for object identification and track matching. The average identification efficiencies are $0.866 \pm 0.010$ and $0.975 \pm 0.018$ for CC and EC electrons, respectively, and $0.940 \pm 0.002$ for muons. The track-matching efficiencies are $0.848 \pm 0.004$ for CC electrons, $0.691 \pm 0.008$ for EC electrons, and $0.950 \pm 0.002$ for muons. Both identification efficiencies and track-matching efficiencies are determined as functions of $p_T$ and $\eta$, applied to each lepton in the $WZ$ MC events. Combined with the acceptance, the overall $WZ$ detection efficiencies are calculated to be (9.92±0.62)%, (11.4±0.9)%, (14.2±0.8)% and (17.6±1.1)% for the final states of $eee$, $ee\mu$, $\mu\mu e$ and $\mu\mu\mu$, respectively.

Using the SM prediction for the $WZ$ diboson cross section, and the measured leptonic decay branching ratios of the $W$ and $Z$ bosons [7], we can calculate the expected signal, which corresponds to 0.22±0.02, 0.22±0.02, 0.26±0.02, 0.33±0.03 events for $eee$, $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ final states, respectively. The uncertainties quoted include statistical and systematic contribution, as well as the uncertainty on luminosity, which is 6.5%.

### D. Estimation of Background

There is no known inherent SM background to $WZ$ diboson decays into three isolated leptons with large transverse momentum. The main background contribution comes from $Z + jets$ events, in which the jets mimic leptons in the detector. This background is estimated using DØ data samples, as follows.

Events are selected using the same criteria as for the $WZ$ sample, except that the requirement for the 3rd lepton is dropped, and these samples therefore include $ee + jets$, $\mu\mu + jets$ and $e\mu + jets$. The rates for jets to mimic electrons or muons are then determined using the QCD dijet data. For the dijet events, the first jet is required to pass the standard DØ jet selection criteria (thus, be considered a “good” jet), and the second jet has to be back-to-back with the first jet. The second jet in each event is used as an unbiased source of jets. Any electrons or muons found within $\Delta R < 0.7$ of the axis of the second jet are regarded as background leptons (most likely these from quark semi-leptonic decays). These lepton (background) rates are calculated as a function of jet $p_T$ and of jet $\eta$. Systematic uncertainty is determined by changing $\Delta R$ by $\pm 0.1$. Applying the lepton (background) rates to jets in the dilepton+jets data yields the total background from multijets, which is then estimated to be $0.292 \pm 0.014$ events.

Another source of background is from $t\bar{t}$ events, which decay into the $W^+W^-b\bar{b}$ final state. The leptonic decay of both $W$ bosons produces a lepton pair and large $\not\!\!E_T$. The semi-leptonic decay of $b$ jets produces the 3rd lepton. This background is estimated using the $t\bar{t}$ Monte Carlo events that pass the $WZ$ event selections. The estimated background contribution from $t\bar{t}$ corresponds to 0.096±0.010 events.

Other sources of background are found to be negligible. The total background is therefore estimated to be 0.39±0.02 events for the integrated luminosities of the data samples used in this analysis.

## IV. FITTING RESULTS

There are 1.02±0.07 $WZ$ events expected in the data, and 0.39±0.02 from estimated background sources. We observed one $WZ$ candidate event in the $\mu\mu\mu$ final state, which is consistent with expectation. Our results are summarized in Table II.

Given the low significance of the signal, we place an upper limit for the $WZ$ inclusive cross section. Following the method described in Ref [7] and [8], we used likelihood method to calculate the limit. The likelihood function is calculated for each final state and then combined for all four states. The upper limit on the $WZ$ production cross section at $\sqrt{s} = 1.96$ TeV is found to be 15.1 pb, corresponding to luminosities of about 138–171 pb$^{-1}$ for the four different trilepton channels. The combined equivalent luminosity of the data sample is about 146 pb$^{-1}$.

| Decay Channel | Number of Candidate | Overall Efficiency | Expected Signal | Estimated Background |
|---|---|---|---|---|
| $eee$ | 0 | 0.099±0.006 | 0.22±0.02 | 0.06±0.01 |
| $ee\mu$ | 0 | 0.114±0.009 | 0.22±0.02 | 0.03±0.01 |
| $\mu\mu e$ | 0 | 0.142±0.008 | 0.26±0.02 | 0.22±0.01 |
| $\mu\mu\mu$ | 1 | 0.176±0.011 | 0.33±0.03 | 0.07±0.01 |
| Total | 1 | – | 1.02±0.07 | 0.38±0.02 |

TABLE II: List of the number of candidate events, overall efficiency, expected signal according to the SM and estimated background in each decay channel.

## V. CONCLUSION

Trilepton final states have been studied in a search for $WZ$ in trilepton events in DØ data collected during 2002 – 2003 in Run II program. According to the SM prediction, the expected signal corresponds to 1.02±0.07 events. The estimated background is 0.39±0.02 events. One trilepton candidate event is observed. This observation is consistent with the SM. The upper limit on the $WZ$ production cross section at $\sqrt{s} = 1.96$ TeV is set at 15.1 pb at the 95% C.L.

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