# Recent Electroweak Results from the Tevatron

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Recent electroweak results from the CDF and DØ Collaborations at the Fermilab Tevatron Collider are presented. After a brief description of the DØ measurements of $W/Z$ production cross sections, $W$ width, $W$ mass and $W \to \tau\nu$ decays, the CDF result on $W(p_T)$ distribution is outlined. The comprehensive search for anomalous gauge couplings by DØ in 1992-96 data is presented along with a detailed description of the $WW/WZ \to \mu\nu$jj channel.

## I. INTRODUCTION

The CDF [1] and DØ [2] collaborations at the Fermilab Tevatron collider collected data during Run I (1992-96) at $\sqrt{s} = 1.8$ TeV corresponding to an integrated luminosity of about 130 $pb^{-1}$ for each experiment. The large number of $W$ and $Z$ bosons detected in the electron and muon channels were used to make precise measurements of their properties. The $W \to \tau\nu$ decay was studied by both experiment to measure the ratio $g_\tau^W/g_e^W$. Using the Run I data, DØ has made a comprehensive search for anomalous trilinear gauge couplings in 12 different diboson channels and has combined them to produce some of the most stringent anomalous gauge coupling limits in the world so far.

Run I was divided into three different sections: Run 1A - 1992-93 ($\sim$ 20 $pb^{-1}$); Run 1B - 1993-95 ($\sim$ 90 $pb^{-1}$); Run 1C - 1995-96 ($\sim$ 20 $pb^{-1}$). After a brief review of $W$ and $Z$ properties in Section II, the DØ search for anomalous gauge couplings in the diboson final states is presented in Section III.

## II. ELECTROWEAK MEASUREMENTS

### A. $W$ and $Z$ Boson Production

Due to cleaner signatures and lower backgrounds, the $W$ and $Z$ bosons are detected via their leptonic decays: $W \to e\nu, \mu\nu$ and $Z \to ee, \mu\mu$. The $W$ event selection requires an electron (muon) with $p_T > 25$ (20) GeV/c and $\not{E}_T$ $> 25$ (20) GeV in the event. For $Z$ selection, the $\not{E}_T$ requirement is replaced by that of a similar second lepton. The backgrounds for the $W$ electron sample are mainly due to QCD fakes (5.7%), $\tau$ decays (1.8%) and one-legged $Z$ decays (0.6%). The total background for the $W$ $\mu$ sample is 19.8% including cosmic muons. The $e$ and $\mu$ $Z$ samples contain 4.8% and 11.6% backgrounds respectively with additional contributions from Drell-Yan pairs and combinatorics.

The recent $W$ and $Z$ cross section results from CDF and DØ are shown in Figure 1 and are compared to the $O(\alpha_s^2)$ theoretical QCD prediction [3]. When the ratio of $W$ and $Z$ cross sections is computed many uncertainties cancel and an indirect measurement of the $W$ width can be made:

$$R_l = \frac{\sigma \cdot B(W \to l\nu)}{\sigma \cdot B(Z \to ll)} = \frac{\sigma(W)}{\sigma(Z)} \frac{\Gamma(W \to l\nu)}{\Gamma(W)} \frac{1}{BR(Z \to ll)}$$

With the measured ratio of $R_l = 10.6 \pm 0.3$, a value of $\Gamma(W) = 2.06 \pm 0.06$ is obtained from the above equation by using the a theoretical calculation of $\sigma_W/\sigma_Z$, the precise measurement of $B(Z \to ll)$ from LEP, and the theoretical computation of $\Gamma(W \to l\nu)$. A comparison of $R_l$ measurements is shown in Figure 1 along with the Tevatron average. An updated and expanded $W/Z$ production results can be found in reference [4].

### B. $W$ Mass

The $W$ boson mass is a fundamental parameter of the Standard Model. In the on shell scheme:

$$M_W = \left(\frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1 - \Delta r}}$$

where $M_Z$ is the Z boson mass, $\alpha$ is the fine structure constant, $\theta_W$ is the weak mixing angle, $G_F$ is the Fermi coupling constant and $\Delta r$ denotes the radiative corrections. The $\Delta r$ is sensitive to masses of particles such as the Higgs boson, top quark and other new particles. Therefore, a precision measurement of the $M_W$ can be used for constraining the Higgs mass or probing the presence of new physics beyond the SM [5].

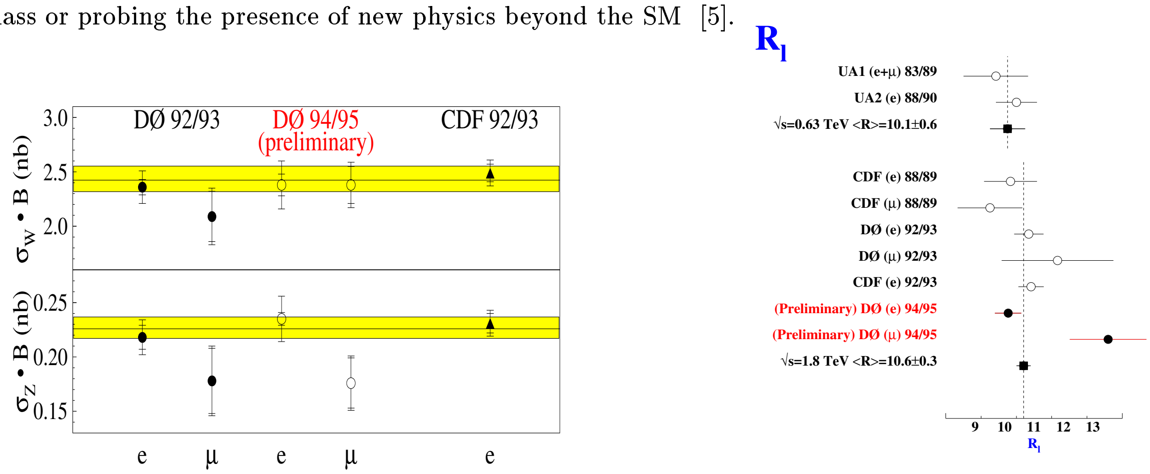


FIG. 1. The Tevatron measurements of $\sigma \cdot B$ for inclusive $W$ and $Z$ production are shown on the left. The shaded bands are the $O(\alpha_s^2)$ theoretical QCD predictions. On the right, a summary of $R_l$ measurements including the Tevatron average.

The $W$ mass is measured using the decay $W \to e\nu$ with a total luminosity of $\int \mathcal{L}dt = 80pb^{-1}$. As an unknown amount of energy goes down the beam pipe in the forward and backward directions, the $p_L(\nu)$ remains uncertain. Hence, the $W$ mass is determined using a likelihood fit to the transverse mass $M_T(e\nu) = [2p_T^e p_T^\nu(1 - cos\phi^{e\nu})]^{1/2}$. A similar procedure is applied to $p_T(e)$ and $p_T(\nu)$ as cross checks.

The event selection and backgrounds are similar to the cross section measurement. Event selection with a high quality isolated electron in the central region with $p_T(e) > 25$ GeV/c, $\not{E}_T > 25$ GeV and hadronic recoil $<$ 15-20 GeV/c leads to a final sample of about 28,000 events. The $p_T(\nu)$ depends on the recoil momentum of the electron and hadrons which relies on the detailed understanding and modelling of the leptonic and hadronic energy scales. The DØ electromagnetic energy scale was calibrated using the constraints from decays $Z \to ee$, $J/\psi \to ee$ and $\pi^0 \to \gamma\gamma$ as shown in Figure 2 where $\alpha$ and $\delta$ are given by $E_{meas} = \alpha E_{true} + \delta$. A complete list of uncertainities contributing to the $W$ mass measurement is listed in Table I.

The fit to the $M_T(e\nu)$ distribution is shown in Figure 2. The arrows indicate the fitted region for the final measurement and the shaded region represents background in the sample. The results from the $M_T(e\nu)$ and $p_T(e)$ fits using the Run 1B data are $80.44 \pm 0.01 \pm 0.07$ and $80.48 \pm 0.11 \pm 0.14$ GeV/$c^2$ respectively. Combining with the 1A measurement, DØ 1A + 1B: $M_W = 80.43 \pm 0.11$ GeV/$c^2$. A summary of direct $M_W$ measurements is shown in Figure 3 along with the world average. Figure 3 also illustrates the constraints imposed by the direct measurements of $M_W$ and $M_t$ by CDF and DØ on the mass of the Higgs boson. Also shown are the indirect SLC/LEP2 and NuTev [6] measurements and the prediction of the Minimal Supersymmetric Model (MSSM). An update DØ $W$ mass measurements including forward detectors can be found in reference [4].

TABLE I. Summary of uncertainities and their sources in the measurement of $M_W$ using a maximum likelihood fit of $M_T(e\nu)$ and $p_T(e)$ distributions (in MeV/$c^2$).

| Source | $M_T$ Fit | $p_T(e)$ Fit | Source | $M_T$ Fit | $p_T(e)$ Fit |
|---|---|---|---|---|---|
| $W$ Statistics | 70 | 85 | Electron Energy Scale | 65 | 65 |
| Calorimeter Linearity | 20 | 20 | Calorimeter Uniformity | 10 | 10 |
| Electron Energy Resolution | 25 | 15 | Electron Angle Calibration | 30 | 30 |
| Electron Removal | 15 | 15 | Selection Bias | 5 | 10 |
| Hadronic Recoil Modelling | 30 | 20 | Input $p_T(W)$ and PDF's | 25 | 70 |
| Radiative Decays | 15 | 15 | Backgrounds | 10 | 20 |
| Total Statistical | 95 | 105 | Total Systematics | 70 | 90 |

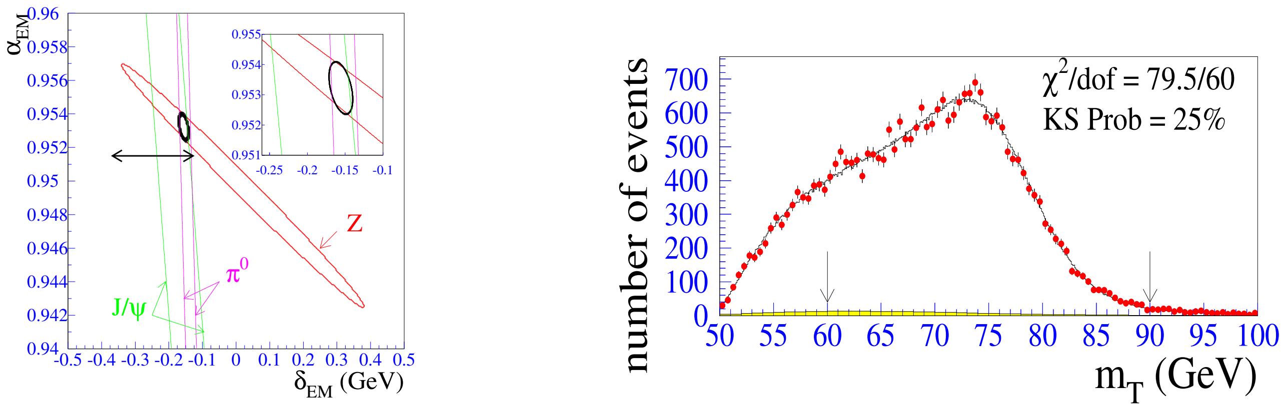


FIG. 2. The left figure shows the constraints on the DØ electromagnetic energy scale parameters from collider data. The transverse mass distribution of $W \to e\nu$ events from DØ Run IB data with the best fit superimposed is shown on the right.

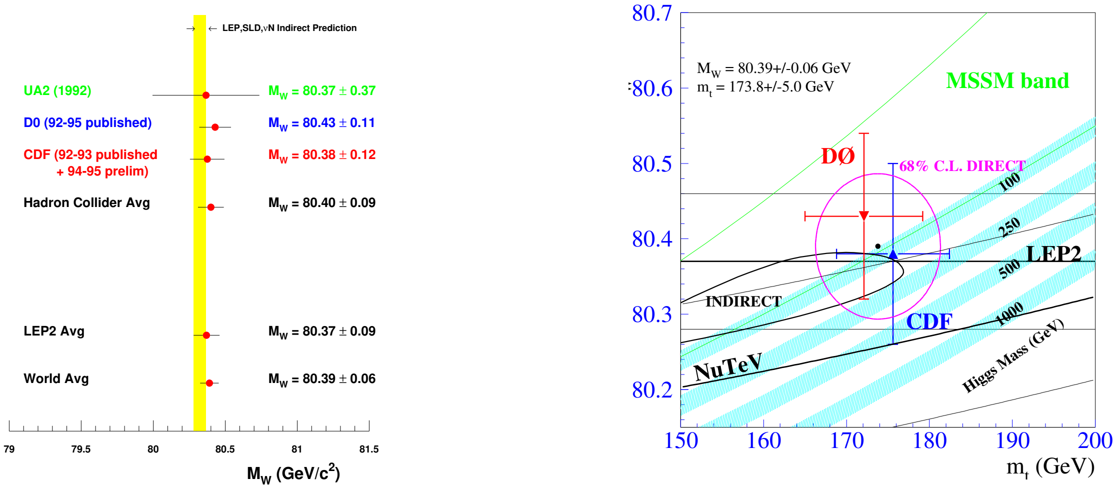


FIG. 3. A summary of direct $M_W$ measurements is shown on the left including the world average. The right figure illustrates the constraints on the Higgs mass imposed by the present Tevatron $M_W$ and $M_t$ measurements as well as by the ones from LEP, NuTeV and SLC. The bands represent the prediction of the MSSM.

### C. $W \to \tau\nu$ and $g_\tau^W/g_e^W$

Both CDF and DØ have measured $W$ production in the mode $W \to \tau\nu$ where $\tau$ decays hadronically. The signature of hadronic decay of the $\tau$ is an isolated narrow jet composed of highly boosted decay products. The event selection requires $E_T(jet) > 25$ GeV/c and $\not{E}_T > 25$ GeV. The signal and QCD backgrounds ($< 20\%$) are estimated using the $E_T(jets)$ profile distribution (fractional $\not{E}_T$ in the two hottest towers of the $\tau$ jet). The DØ preliminary results are $\sigma \cdot BR(W \to \tau) = 2.38 \pm 0.09\ (stat) \pm 0.10\ (sys) \pm 0.1\ (lum)$ nb and $g_\tau^W/g_e^W = 1.004 \pm 0.032$.

The CDF collaboration having a silicon vertex detector has used the decay $\tau \to e\nu\nu$ to measure $R_{BR} = BR(W \to \tau\nu)/BR(W \to e\nu)$. The technique is based on the difference in electron impact parameter distributions in a sample of single electron events composed of $W \to e\nu$ decays, $W \to \tau\nu$, $\tau \to e\nu\nu$ decays and QCD backgrounds. A likelihood fit to the branching fraction $R_{BR}$ is performed using $f(d_0; b, c) = af_e(d_0) + bf_\tau(d_0) + cf_{bkg}(d_0)$ where the relevant impact parameter distributions $f_e(d_0)$, $f_\tau(d_0)$ are extracted from Monte Carlo and $f_{bkg}(d_0)$ from QCD data. The results are $R_{BR} = 1.03^{+0.38}_{-0.32} \pm 0.18$ and $g_\tau^W/g_e^W = 1.01 \pm 0.17 \pm 0.09$ consistent with hadronic $\tau$ decay measurements and $\tau - e$ universality.

### D. $W(p_T)$ Distribution

The CDF collaboration has measured the $p_T(W)$ distribution in the decay mode $W \rightarrow e\nu$ using Run I data ($\int \mathcal{L} dt = 110\ pb^{-1}$). The measurement goals are to test perturbative QCD at large $p_T$ ($>$ 20 GeV/c) and differentiate gluon resummation techniques [7] (such as q-t-space *vs* b-space) at small $p_T$ ($<$ 10 GeV/c). Moreover the knowledge of the $W/Z$ production is essential for the search for new physics and is a source of systematics for the measurements of $M_W$, $\Gamma_W$, etc. The event selection demands an electron with $p_T(e) \geq 25$ GeV/c and $\not{E}_T \geq 25$ GeV. The major backgrounds ($< 15\%$) are due to QCD electron fakes, $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ and the one-legged decays of $Z \rightarrow ee$.

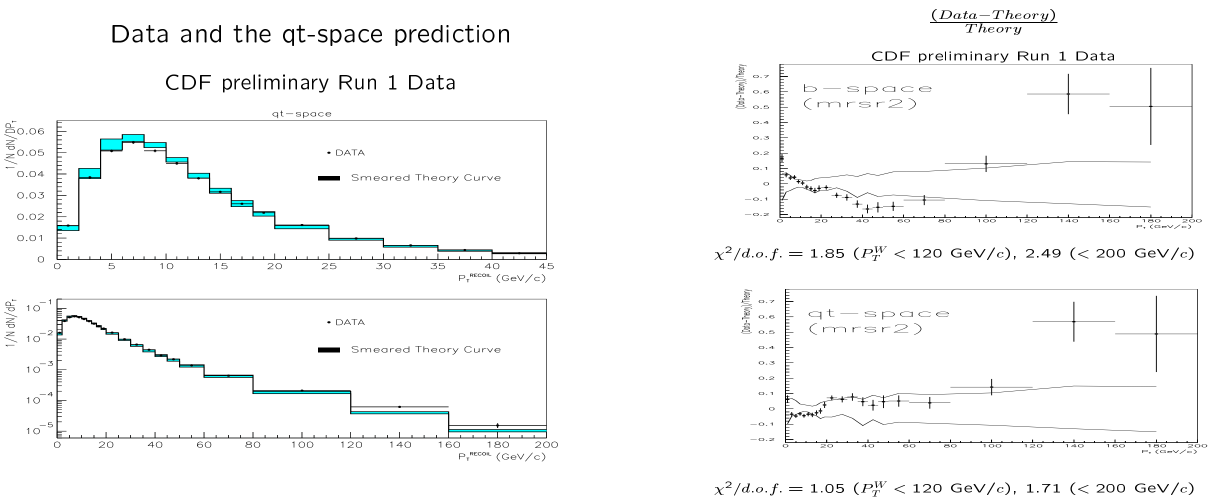


FIG. 4. The comparison of data and theoretical predictions using the qt-space gluon resummation technique for $p_T(W)$ distribution (CDF) is shown on the left. On the right, the ratio (Data-Theory)/Theory is plotted as a function of $p_T(W)$ using the q-t-space and b-space gluon resummation methods.

The $p_T(W)$ distribution using qt-space gluon resummation technique is shown in Figure 4. Figure 4 also displays the ratio (data-theory)/theory *vs* $p_T(W)$ for both resummation techniques. The theory distributions used are obtained by adding the single boson backgrounds and are smeared with detector resolutions while the data distributions are after the subtraction of the QCD background. Both resummation techniques agree with data up to $p_T(W) \approx 120$ GeV. At higher $p_T(W)$ region, there appears to be some discrepancy as in the case of CDF $Z \rightarrow ee$ data [8]. The recently completed DØ $W(p_T)$ measurements can be found in reference [9].

## III. SEARCH FOR ANOMALOUS GAUGE COUPLINGS

The effective CP conserving Lagrangian for the description of anomalous gauge couplings (AGC) is given by [10]:

$$iL_{eff}^{WWV} = g_{WWV}\{g_1^V(W_{\mu\nu}^{\dagger}W^{\mu} - W^{\dagger\mu}W_{\mu\nu})V^{\nu} + \kappa_V W_{\nu}^{\dagger}W_{\nu}V^{\mu\nu} + (\lambda/m_W^2)W_{\rho\mu}^{\dagger}W_{\nu}^{\mu}V^{\nu\rho}$$
$$+ ig_5^V \epsilon_{\mu\nu\rho\sigma}[(\partial^{\rho}W^{\dagger\mu})W^{\nu} - W^{\dagger\mu}(\partial^{\rho}W^{\nu})]V^{\sigma}\}$$

where V = Z, $\gamma$. If CP violating terms are allowed, three additional terms will appear in the above Langrangian. The overall couplings are defined as $g_{WW\gamma}$ = e and $g_{WWZ}$ = e $\cot\theta_W$. At tree level in the SM, the parameters are uniquely determined: $g_1^Z = g_1^{\gamma} = \kappa_Z = \kappa_{\gamma} = 1, \lambda_Z = \lambda_{\gamma} = g_5^Z = g_5^{\gamma} = 0$. For on-shell photons, $g_1^{\gamma} = 1$ and $g_5^{\gamma} = 0$ are fixed by electromagnetic gauge invariance while $g_1^Z$ and $g_5^Z$ may, however, differ from their SM values. The deviations from tree level SM values can be cast as: $\Delta g_1^Z = (g_1^Z - 1), \Delta\kappa_{\gamma} = (\kappa_{\gamma} - 1), \Delta\kappa_Z = (\kappa_Z - 1), \lambda_{\gamma}, \lambda_Z, g_5^Z$. Most theoretical arguments suggest that these anomalous couplings are significant at $O(m_W^2/\Lambda^2)$ where $\Lambda$ is the scale of new physics. To avoid unitarity violations the coupling parameters should be expressed as form factors such as: $\lambda(\hat{s}) = \lambda/(1 + \hat{s}/\Lambda_{FF}^2)^2$; $\Delta\kappa(\hat{s}) = \Delta\kappa/(1 + \hat{s}/\Lambda_{FF}^2)^2$ with $\Lambda_{FF}$ as the form factor scale. The tree level Feynman diagrams for $p\overline{p} \rightarrow WW/WZ$ production at the Tevatron are shown in Figure 5.

Limits on these couplings are usually obtained under the assumption of equal couplings for $WW\gamma$ and $WWZ$ ($g_1^\gamma = g_1^Z = 1, \Delta\kappa_\gamma = \Delta\kappa_Z$, and $\lambda_\gamma = \lambda_Z$). In the literature, another set of relations is frequently used, the HISZ relations [11] where the $WWZ$ and $WW\gamma$ couplings are related by: $\Delta\kappa_Z = \Delta\kappa_\gamma(1-\tan^2\theta_W)/2$; $\Delta g_{1Z} = \Delta\kappa_\gamma/2\cos^2\theta_W$; $\lambda_Z = \lambda_\gamma$.

The evidence for non SM physics contributions will be an enhancement in the high $p_T(W)$ region [12]. Figure 5 illustrates the predicted number of events in the mode $WW/WZ \to \mu\nu$jj (for Run 1B) *vs* the $p_T(W)$ as a comparison of SM and non SM physics (for $\lambda = 1$ and $\Delta\kappa = 1$). Therefore, a study of the $p_T(W)$ spectrum of $WW/WZ$ production will provide a sensitive test of the $WWZ$ and $WW\gamma$ couplings.

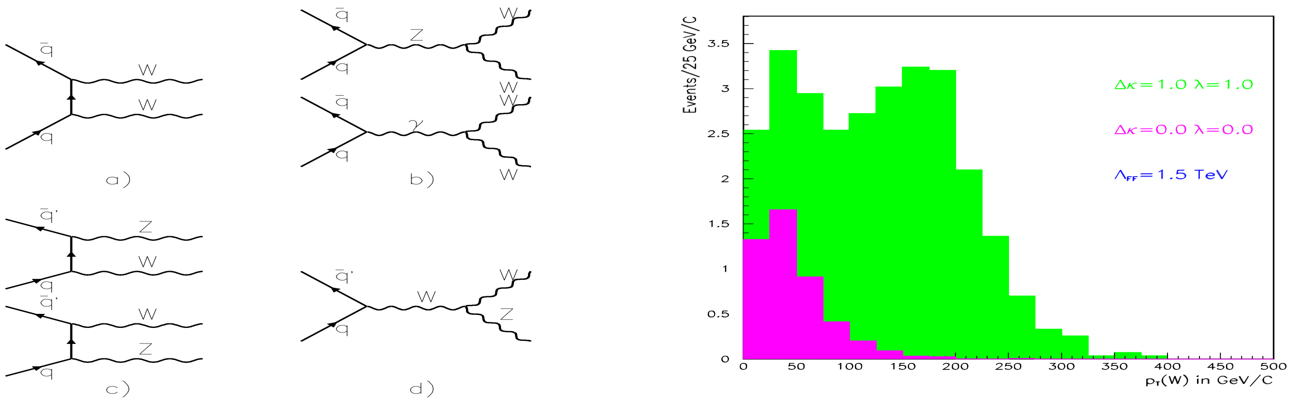


FIG. 5. The tree level Feynman diagrams for $p\overline{p} \to WW/WZ$ production at the Tevatron are shown on the left. The right figure shows the comparison of the Standard Model and Anomalous Gauge Coupling predictions for $\int\mathcal{L}dt = 80.7\ pb^{-1}$ at the DØ Run I detector in the channel $WW/WZ \to \mu\nu$jj.

### A. $WW/WZ \to \mu\nu$jj

The 1994-95 data with $\int\mathcal{L}dt = 80.7\ pb^{-1}$ were used in the search for anomalous $WW/WZ$ production in the mode $WW/WZ \to \mu\nu$jj. The event selection requires a high $p_T$ muon (> 20 GeV/c), $\not{E}_T > 20$ GeV and at least two good jets with $p_T(jet) > 20$ GeV/c. There is no differentiation between the two processes $W \to$ jj and $Z \to$ jj due to limited mass resolution of the calorimeter. The invariant mass of the two highest $E_T$ jets in the event is required to be between 50 and 110 GeV/$c^2$ along with a constraint on the transverse mass $M_T(\mu\nu) = [2 \cdot E_T^\mu \cdot \not{E}_T \cdot (1-\cos(\phi_\mu - \phi_\nu))]^{1/2} >$ 40 GeV/$c^2$. The final event count is $224 \pm 15$ while the SM prediction is $4.5 \pm 0.8$ events.

The major sources of backgrounds are from QCD multijet and $W+ \geq 2$ jet events with $W \to \mu\nu$. The QCD multijet background is due to misidentifying a muon contained in one of the jets as an isolated muon and where there is significant $\not{E}_T$. This background is estimated from data using a control sample to determine muon fake probability [13]. The $W+ \geq 2$ jets contribution is computed using a Monte Carlo sample generated with VECBOS, HERWIG [14] (hadronization) and 0GEANT [15] for detector simulation. Normalization of this background is determined by comparing the number of expected events outside the dijet mass window after the subtraction of the QCD multijet contribution. The final background contributions are $105 \pm 19$ (QCD multijet), $117 \pm 24$ ($W+ \geq 2$ jets) and $2.7 \pm 1.2$ (others) without systematics. The total background contribution to the final sample are $224.5 \pm 32.7\ \pm 45.8$.

TABLE II. The DØ Run IB $WW/WZ \to \mu\nu$jj axis limits (one-dimentional) at the 95% confidence limits (C.L.) with the assumption of equal $WW\gamma$ and $WWZ$ couplings and the HISZ relations. The limits are listed for two different values of $\Lambda_{FF}$ along with the relevant unitary bounds.

| 95% C.L. Limits | $\Lambda_{FF} = 1.5$ TeV | Unitary Bounds | $\Lambda_{FF} = 2.0$ TeV | Unitary Bounds |
|---|---|---|---|---|
| $\lambda_\gamma = \lambda_Z$ $(\Delta\kappa_\gamma = \Delta\kappa_Z = 0)$ | -0.45, 0.46 | -0.82 0.82 | -0.43, 0.44 | -0.46, 0.46 |
| $\Delta\kappa_\gamma = \Delta\kappa_Z$ $(\lambda_\gamma = \lambda_Z = 0)$ | -0.62, 0.78 | -1.17, 1.17 | -0.60, 0.74 | -0.66, 0.66 |
| $\lambda_\gamma$(HISZ) $(\Delta\kappa_\gamma = 0)$ | -0.44, 0.46 | -0.82, 0.82 | -0.42, 0.44 | -0.46, 0.46 |
| $\Delta\kappa_\gamma$(HISZ) $(\lambda_\gamma = 0)$ | -0.75, 0.99 | -2.17, 2.17 | -0.71, 0.96 | -1.22, 1.22 |

The comparison of the final data sample and the total background as a function of $p_T(W)$ is shown in Figure 6. The data and background distributions are consistent with each other signalling no evidence of AGC. This agreement is translated into AGC limits by means of a binned maximum likelihood method with convoluting Gaussian errors for the prediction and background uncertainities. The 95% C. L. limits for the coupling parameters $\lambda$ and $\Delta\kappa$ are tabulated in Table II for the cases of equal $WWZ$ and $WW\gamma$ couplings and the HISZ relations. The contour constraining the coupling parameters in the $\lambda - \Delta\kappa$ plane is illustrated in Figure 6 for $\lambda_{WW\gamma} = \lambda_{WWZ}$ and $\Delta\kappa_{WW\gamma} = \Delta\kappa_{WWZ}$.

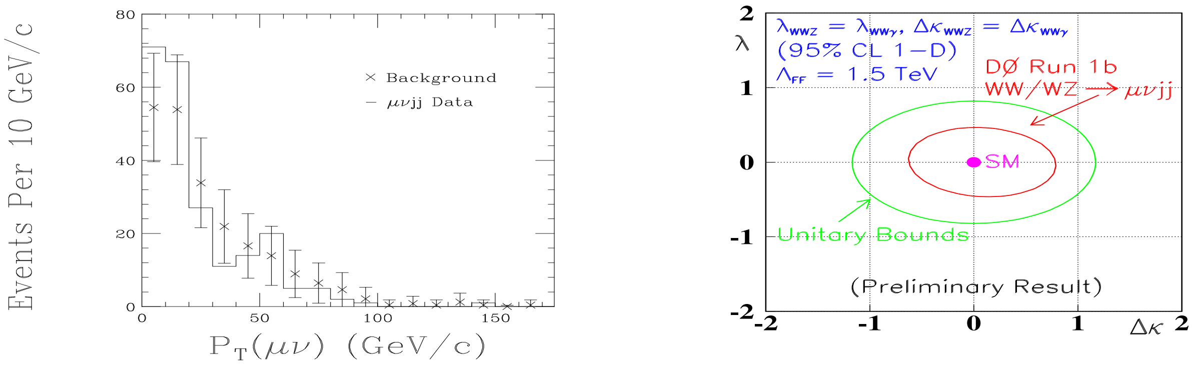


FIG. 6. Comparison of the final data sample and estimated total background as function of $p_T(W)$ for $WW/WZ \to \mu\nu$jj is shown on the left. On the right, the contour plot of allowed region in the $\lambda - \Delta\kappa$ plane at 95% C.L. for $\Lambda = 1.5$ TeV. The outer ellipse shows the bounds imposed by the relevant unitary conditions.

### B. Overview of the DØ Diboson Projects

The DØ collaboration has done a comprehensive search [16] for anomalous gauge couplings in the four diboson final states $p\bar{p} \to WW, WZ, W\gamma, Z\gamma$ in twelve different decay modes using Run I data. A detailed listing of the diboson final states and the relevant decay channels including the status of the searches is given in Table III. The limits from all different channels have been combined to produce the final AGC coupling limits from DØ in Run I.

### C. Run I DØ Combined Anomalous Coupling Limits

The combined limit of $WW/WZ \to \mu\nu$jj channel along with 11 other channels listed in Table III has been produced. This involves performing a simultaneous binned maximum likelihood fit to the observed number of events and the expected number of signal and background distributions: $p_T(\gamma)$ spectrum in the $W\gamma$ channels, $p_T(l)$ distribution in $WW \to l\nu l\nu$ modes, $p_T(W \to l\nu)$ spectrum in the $WW/WZ \to l\nu$jj channels and to the observed number of events in the $WZ \to l\nu ee$ after a careful account of correlated and uncorrelated uncertainities in different data sets and modes. The one-dimensional 95% C.L. axis limits for the various coupling cases are given in Table IV.

TABLE III. A summary of the comprehensive search for anomalous trilinear gauge couplings by DØ using Run I data in 12 different channels.

| Diboson State | Channel | Coupling | Status |
|---|---|---|---|
| $Z\gamma$ | $\to ee\gamma, \mu\mu\gamma$ | $Z\gamma\gamma, ZZ\gamma$ | Published |
| | $\to \nu\nu\gamma$ | | '93-94 Data: published ('94-95 Data: in progress) |
| $W\gamma$ | $\to e\nu\gamma, \mu\nu\gamma$ | $WW\gamma$ | Published |
| $WW$ | $\to e\nu e\nu, e\nu\mu\nu, \mu\nu\mu\nu$ | $WW\gamma, WWZ$ | Published |
| $WZ$ | $\to e\nu ee, \mu\nu ee$ | $WWZ$ | Completed |
| $WW/WZ$ | $\to e\nu$jj | $WW\gamma, WWZ$ | Published |
| | $\to \mu\nu$jj | | Completed |
| Combined Limit | All completed | $Z\gamma\gamma, ZZ\gamma, WW\gamma, WWZ$ | Completed except '94-95 $Z(\nu\nu)\gamma$ |

## IV. SUMMARY AND OUTLOOK

The CDF and DØ collaborations have done a number of world class measurements of electroweak parameters using 1992-96 data such as $R_{e+\mu} = 10.48 \pm 0.43$, $\Gamma_W = 2.126 \pm 0.092$ GeV (indirect), $M_W = 80.43 \pm 0.11$ GeV, $g_\tau^W/g_e^W = 1.004 \pm 0.032$. The diboson channels $WW/WZ \to \mu\nu$jj, $WZ \to \mu\nu ee$, $e\nu ee$ have been completed. Combined with other DØ channels previously announced, these provide some of the most stringent limits on the anomalous coupling parameters. Looking towards future, the Main Injector is close to operation. The CDF and DØ detectors are undergoing major upgrades. We expect much larger data sets with much improved detectors in Run II. Both collaborations are looking forward to an exciting Run II with many precision measurements and new discoveries.

TABLE IV. The DØ Run I combined 1-D limits at 95% C.L. from a simultaneous fit to the $W\gamma$, $WW \to$ dileptons, $WW/WZ \to e\nu$jj, $\mu\nu$jj, and $WZ \to$ trilepton data samples for four different relations between $WWZ$ and $WW\gamma$ couplings.

| 95% C.L. Limits | $\Lambda = 1.5$ TeV | $\Lambda = 2.0$ TeV |
|---|---|---|
| $\lambda_\gamma = \lambda_Z$ ($\Delta\kappa_\gamma = \Delta\kappa_Z = 0$) | -0.20, 0.20 | -0.18, 0.19 |
| $\Delta\kappa_\gamma = \Delta\kappa_Z$ ($\lambda_\gamma = \lambda_Z = 0$) | -0.27, 0.42 | -0.25, 0.39 |
| $\lambda_\gamma$(HISZ) ($\Delta\kappa_\gamma = 0$) | -0.20, 0.20 | -0.18, 0.19 |
| $\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma = 0$) | -0.31, 0.56 | -0.29, 0.53 |
| $\lambda_Z$(SM $WW\gamma$) ($\Delta\kappa_Z = \Delta g_1^Z = 0$) | -0.26, 0.29 | -0.25, 0.27 |
| $\Delta\kappa_Z$(SM $WW\gamma$) ($\lambda_Z = \Delta g_1^Z = 0$) | -0.37, 0.55 | -0.34, 0.51 |
| $\Delta g_1^Z$(SM $WW\gamma$) ($\lambda_Z = \Delta\kappa_Z = 0$) | -0.46, 0.65 | -0.44, 0.61 |
| $\lambda_\gamma$(SM $WWZ$) ($\Delta\kappa_\gamma = 0$) | -0.27, 0.25 | -0.25, 0.24 |
| $\Delta\kappa_\gamma$(SM $WWZ$) ($\lambda_\gamma = 0$) | -0.57, 0.74 | -0.54, 0.69 |

## V. ACKNOWLEDGEMENT

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