Fermi National Accelerator Laboratory

FERMILAB-Conf-97/218-E
CDF and DØ

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C.E. Gerber
For the CDF and DØ Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

June 1997

Published Proceedings of the *5th Topical Seminar on the Irresistible Rise of the Standard Model*, San Miniato al Todesco, Italy, April 21-25, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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Production of Gauge Bosons at the Tevatron

C. E. Gerber[a] *

[a]Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510, USA

The CDF and DØ collaborations have used recent data taken at the Tevatron to perform QCD tests with W and Z bosons decaying leptonically. DØ measures the production cross section times branching ratio for W and Z bosons and determines the branching ratio $B(W \to l\nu\ ) = (10.43 \pm 0.44)\%\ \ (l = e, \mu)$. This also gives an indirect measurement of the total width of the W boson: $\Gamma_W = 2.16 \pm 0.09$ GeV. The W cross section times branching ratio into tau leptons is measured to be $\sigma(\overline{p}p \to W + X)B(W \to \tau\nu\ ) = 2.38 \pm 0.13$ nb, from which the ratio of the coupling constants is determined: $g_\tau^W / g_e^W = 1.004 \pm 0.019 \pm 0.026$. DØ's measurement of the differential $d\sigma/dP_T$ distribution for the Z boson decaying to electrons, discriminates between different phenomenologic vector boson production models. CDF measures the cross section for the Drell–Yan continuum, and extracts improved limits on compositeness scales for quarks and leptons of $\Lambda_{ql} \sim 3 - 6$ TeV, depending on the model. Studies of $W + Jet$ production at CDF and DØ find that the QCD prediction underestimates the production rate of $W + 1\ Jet$ events by about a factor of 2 as measured by both collaborations.

1. INTRODUCTION

W and Z bosons, the carriers of the weak force, are directly produced in high energy $\overline{p}p$ collisions at the Fermilab Tevatron, operating at a center of mass energy of $\sqrt{s} = 1.8$ TeV . In addition to probing Electroweak Physics, the study of the production of W and Z bosons provides an avenue to explore QCD, the theory of Strong Interactions. The benefits of using intermediate vector bosons to study perturbative QCD are large momentum transfer, distinctive event signatures, low backgrounds, and a well understood electroweak vertex.

Large number of W bosons have been detected by the two collider detectors (CDF and DØ), during the 1992–1996 running period. These large samples of W bosons complement the detailed studies carried out on the Z boson at LEP and SLC, and also the new W studies from LEP II. The CDF and DØ collaborations have used these large data samples to perform various tests of the Standard Model. Their preliminary results are presented in the next sections.

*For the CDF and DØ collaborations.

2. W AND Z PRODUCTION CROSS SECTIONS AT DØ

The W and Z production cross sections times leptonic branching fractions are measured using data collected by the DØ detector during 1994–1995, in the electron, muon and tau channels. The W candidates decaying to electrons or muons were selected as events containing one high quality isolated lepton and an imbalance of the momentum in the transverse plane of at least 25 GeV for electrons and 20 GeV for muons, as a signal for the undetected neutrino. The Z candidates decaying to electrons or muons were selected as events containing two high quality isolated leptons.

The major source of background in all four cases is due to QCD events with jets faking leptons. The amount of background in the samples is estimated directly from collider data. Backgrounds originating from other physics processes ($W \to \tau\nu$, $Z \to \tau\tau$, Drell–Yan) are estimated from Monte Carlo. Lepton selection efficiencies are determined from the $Z \to ll$ data. The geometric and kinematic acceptance is calculated from a fast Monte Carlo simulation of the DØ detector. Table 1 shows the preliminary values for the cross sections measured from these samples.

Table 1
The DØ preliminary cross sections for W and Z bosons.

	$W \to e\nu$	$Z \to ee$	$W \to \mu\nu$	$Z \to \mu\mu$
N_{obs}	59579	5705	4472	173
Background(%)	8.1 ± 0.9	4.8 ± 0.5	18.6 ± 2.1	8.0 ± 2.1
Efficiency(%)	70.0 ± 1.2	75.9 ± 1.2	24.7 ± 1.5	43.2 ± 3.0
Acceptance(%)	43.4 ± 1.5	34.2 ± 0.5	20.1 ± 0.7	5.7 ± 0.5
Luminosity [pb^{-1}]	75.9 ± 6.4	89.1 ± 7.5	32.0 ± 2.7	32.0 ± 2.7
$\sigma \cdot B$ [nb] ($\pm$stat)	2.38 ± 0.01	0.235 ± 0.003	2.28 ± 0.04	0.202 ± 0.016
($\pm$syst) ($\pm$lum)	$\pm 0.09 \pm 0.20$	$\pm 0.005 \pm 0.020$	$\pm 0.16 \pm 0.19$	$\pm 0.020 \pm 0.017$

Many common sources of systematic error cancel when taking the ratio of the W to Z production cross section times branching ratio, defined as

$$R \equiv \frac{\sigma(\bar{p}p \to W + X) B(W \to l\nu\ )}{\sigma(\bar{p}p \to Z + X) B(Z \to ll\ ).}$$

This ratio is of interest since it can be expressed as the product of calculable or well measured quantities:

$$R = \frac{\sigma_W}{\sigma_Z} \quad \frac{\Gamma(W \to l\nu)}{\Gamma(Z \to l^+l^-)} \quad \frac{\Gamma_Z}{\Gamma_W}.$$

For the combined electron and muon channels, DØ measures

$$R = 10.32 \pm 0.43.$$

Using the LEP measurement[1] of $B(Z \to ll\ ) = (3.367 \pm 0.006)\%$, and the theoretical calculation[2] of $\sigma_W/\sigma_Z = 3.33 \pm 0.03$, one obtains

$$B(W \to l\nu\ ) = (10.43 \pm 0.44)\%.$$

Combining this result with a theoretical calculation of the W leptonic partial width[3] $\Gamma(W \to l\nu\ ) = 225.2 \pm 1.5$ MeV, results in a total width for the W boson of

$$\Gamma(W) = 2.159 \pm 0.092 \text{ GeV}.$$

This method gives the most precise indirect measurement of the width of the W boson (Γ_W) currently available. All these results are in good agreement with previous DØ results[4], and with Standard Model predictions.

DØ has also observed the production of $W \to \tau\nu$ and used it to test lepton universality. The τ lepton is identified via its hadronic decay, which is detected as an isolated, narrow jet, with $E_T(jet) > 25$ GeV and completely contained within DØ's central calorimeter. In addition, to select $\tau's$ originating from W decays, a minimum imbalance in the transverse energy of 25 GeV is required. The Profile distribution, defined as the sum of the two highest E_T towers divided by the transverse energy of the cluster, provides powerful discrimination against QCD multijet backgrounds. Jets originating from hadronic τ decays tend to be narrower than those originating in multijet QCD events, and therefore will show a higher value for the Profile distribution. Figure 1 shows the Profile distribution for τ candidates (before the Profile cut), and for QCD background events. The shaded low–Profile region is used to estimated the QCD contamination in the final $W \to \tau\nu$ sample.

Events where more than one inelastic collision took place during the same beam crossing were rejected at the trigger level; this effectively reduced the integrated luminosity to $\approx$ 17 pb^{-1} for the complete 1994–1995 DØ data sample. 1202 events pass these selection criteria, with estimated backgrounds of $106 \pm 7 \pm 5$ events from QCD, 81 ± 14 events from noisy calorimeter cells, 32 ± 5 events from $Z \to \tau\tau$, and 3 ± 1 events from $W \to e\nu$. The acceptance $\times$ efficiency for the selection is $\approx$ 3.8%. The preliminary cross section times branching ratio obtained from this data is

$$\sigma(\bar{p}p \to W + X) B(W \to \tau\nu\ ) = 2.38$$

$$\pm 0.09 \text{ (stat)} \pm 0.10 \text{ (syst)} \pm 0.20 \text{ (lum)nb}.$$

Comparing this measurement with DØ's published [4] value for $\sigma \cdot B(W \to e\nu\ )$, measures the

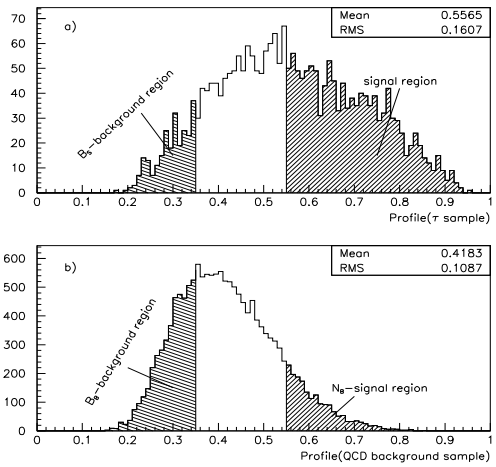

Figure 1. DØ Profile Distribution for τ candidates (Top) and for QCD multijet background events (Bottom).

ratio of the couplings

$$g_\tau^W / g_e^W = 1.004 \pm 0.019 \pm 0.026.$$

This result shows good agreement with the expected $e - \tau$ universality.

DØ also measures the differential $d\sigma/dP_T$ cross section for the Z boson decaying to electrons, as a function of the boson transverse momentum. This measurement provides a sensitive test of the resummation formalism used in low P_T vector boson production phenomenology. The same data set as the one in the inclusive production cross section measurement is used for this analysis. The shape of the background as a function of P_T^Z is obtained directly from DØ direct photon data. The uncertainties in shape and level of background are conservatively assigned to be 50% for each bin in P_T. The variation of the acceptance and efficiency vs P_T^Z is calculated using a Monte Carlo simulation.

The resulting distribution for the differential cross section, normalized to the inclusive measurement is shown in figure 2, compared to theoretical predictions by Ladinsky and Yuan [5], and Arnold and Kauffman [6]. Both predictions use MRSA structure functions and are smeared with the DØ detector resolution. A comparison of the smeared predictions to DØ data, shows a better agreement with the former [5] ($\chi^2_{dof} = 1.25$), than the latter [6] ($\chi^2_{dof} = 9.2$).

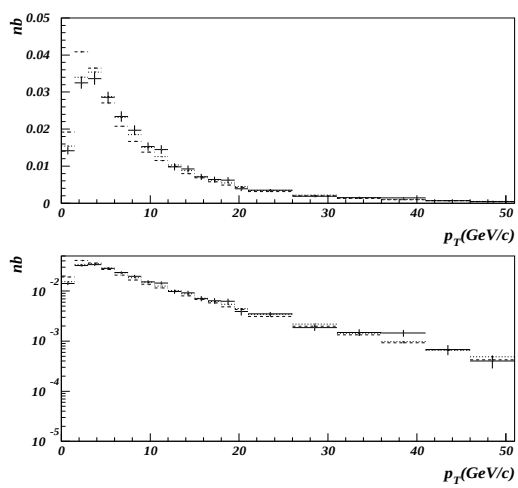

Figure 2. DØ data (full line), compared to theoretical prediction by Ladinsky–Yuan[5] (dotted) and Arnold–Kauffman[6] (dashed).

3. DRELL–YAN CONTINUUM PRODUCTION AT CDF

CDF measures $d^2\sigma/dMdy$ ($|y| < 1$) for dileptons pairs produced in the process $\overline{p}p \to l^+l^- + X$, using 110 pb^{-1} of dielectron and dimuon data taken during the 1992–1996 Tevatron run. If quarks and leptons are composite and have a common substructure, the dilepton mass spectrum in $\overline{p}p \to l^+l^- + X$ interactions will show an excess relative to the Standard Model Drell–Yan expectation at high masses.

The event selection requires the presence of two

opposite charged, isolated, central leptons (electrons or muons), with $E_T^l > 20$ GeV and invariant mass of the dilepton pair of at least 50 GeV. The major sources of background are QCD multijet events and Diboson and Top production processes; they are estimated directly from collider data.

Figure 3 shows CDF's result. The circles ($M <$ 50 GeV) correspond to earlier data [7]. The diamonds and crosses, respectively, are the dielectron and dimuon data, normalized in the 50 to 150 GeV mass range to the Standard Model NLL prediction from [8]. The lack of any significant deviation from the Standard Model prediction is used to set a limit on quark–lepton compositeness scales.

To establish a compositeness scale, any deviation of the data from the Drell–Yan prediction is assumed to be due to composite fermions. At collision energies well below the mass scale of compositeness, quark and lepton substructure can be described by an effective four–fermion contact interaction. CDF adds the ELHQ[9] contact lagrangian to the Standard Model Drell–Yan amplitudes to calculate the cross section used to determine the compositeness scale. The various compositeness models considered are categorized by the signed interaction strengths; the two models giving the largest differences are shown in figure 3. The observed number of events for $M > 150$ GeV are compared against model predictions using a binned likelihood method. This allows the setting of improved limits on compositeness scales of

$$\Lambda_{ql} \sim 3 - 6 \text{ TeV},$$

at single sided 95% CL limit for the combined e, μ data, depending on the model.

4. STUDIES OF $W + JETS$ PRODUCTION AT CDF AND DØ

The CDF Collaboration uses 108 pb^{-1} of data, accumulated from 1992 to 1995, to measure the production cross section of $\sigma_n^e \equiv W+ \geq n\ Jets$ (for $n = 1, 4$) relative to the published ($W+ \geq 0\ Jets$) inclusive cross section measurement for the 1992–1993 collider run [10]. The analysis is restricted to events where the W decays into a

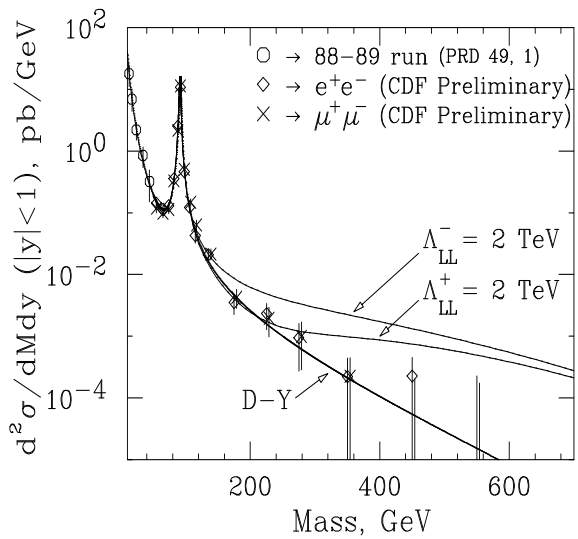

Figure 3. CDF Drell–Yan data, compared to the Standard Model prediction by[7], and two compositeness models giving the largest differences.

central pseudorapidity electron ($|\eta_e| < 1.1$). The jets are reconstructed using a 0.4 fixed cone algorithm and restricted to $|\eta_{Jet}| < 2.4$.

The backgrounds to this sample are determined as a function of jet multiplicity in the event. The dominant background is due to QCD multijet events, and varies from $\approx 2.9\%$ to $\approx 27\%$ for the $n = 0$ to $n = 4$ case. The background originating from Top and Diboson production processes varies from $\approx 0.1\%$ to $\approx 17\%$ for the $n = 0$ to $n = 4$ case. Backgrounds from electroweak processes ($W \to \tau\nu$, $Z \to \tau\tau$ and $Z \to e\not{e}$) are estimated as a flat 3% contribution. The overall detection efficiency is $\approx 20\%$.

The measurement of σ_n^e is compared to predictions obtained from the leading order QCD matrix element calculations by including gluon radiation and hadronic fragmentation using the HERWIG [11] shower simulation algorithm. The W boson events with hadron showers are then introduced into a full CDF detector simulation, and the resulting jets are identified and selected as in the data, allowing a comparison between the

QCD predictions and the data.

Figure 4 shows CDF's data compared to the theoretical prediction for two choices of the renormalization and factorization scale $Q^2_{REN,FAC}$. The published $Z+ \geq n\ Jets$ cross section from reference [12] are also shown. One observes that the measured $W+ \geq n\ Jets$ cross sections are a factor of 1.7 larger than the LO QCD prediction for $Q^2_{REN,FAC} = M^2(W) + p_T^2(W)$.

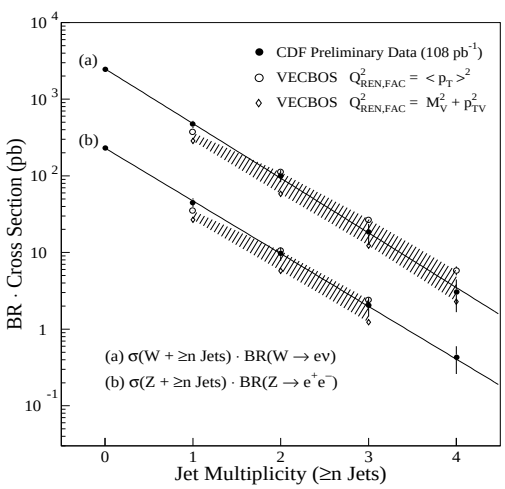

Figure 4. CDF's $\sigma_n^e(W + n\ Jets)$ as a function of the jet multiplicity. The published result[12] for $\sigma_n^e(Z + n\ Jets)$ is also shown.

CDF data is also used to compare different distributions of jets produced with a W boson to QCD predictions. Figure 5 shows the measured E_T distribution for the leading to fourth–leading jet in events of $W+ \geq 1$ to $W+ \geq 4\ Jets$ respectively. The error bars shown for the data include statistical uncertainties and background subtraction systematics. The shape of the jet E_T distributions are well reproduced by the theoretical prediction. The invariant mass distribution of the two leading jets and the ΔR separation between the two leading jets is also well reproduced by QCD.

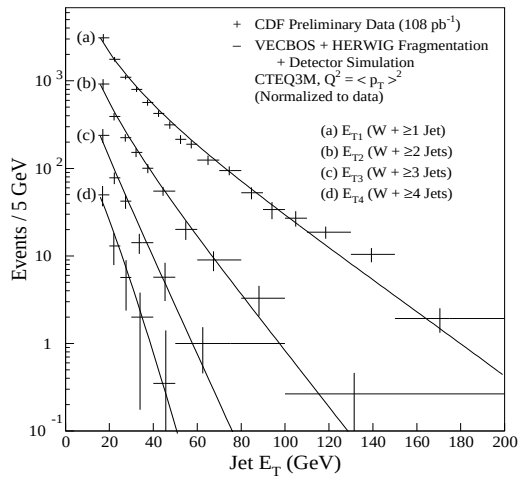

Figure 5. The shape of the jet E_T distributions for the leading to fourth–leading jet in events of $W+ \geq 1$ to $W+ \geq 4\ Jets$ is well reproduced by QCD.

The DØ Collaboration uses its inclusive 1994–1995 $W \to e\nu$ sample to measure R_{10}, the exclusive ratio of the $W+1\ Jet$ to $W+0\ Jet$ production cross section as a function of jet E_T threshold in the 20 to 60 GeV range. The analysis is restricted to events where the W decays into a central pseudorapidity electron ($|\eta_e| < 1.0$). The jets are reconstructed using a 0.7 fixed cone algorithm and restricted to $|\eta_{Jet}| < 2.4$.

The backgrounds to this sample are determined as a function of jet E_T threshold (E_T^{min}) for both the $W + 1\ Jet$ and the $W + 0\ Jet$ case. The dominant background is due to QCD multijet events, which stays below 2% for all thresholds in the $W + 0\ Jet$ case, and varies from $\approx 5\%$ to $\approx 20\%$ for E_T^{min} of 20 to 60 GeV in the $W + 1\ Jet$ case. The backgrounds originating from other physics processes do not exceed the 2% level for all E_T^{min}. The variation of the selection efficiency

as a function of E_T^{min} is estimated using DØ's $Z \to ee$ sample. The uncertainty in the efficiency introduces a systematic uncertainty of $\approx 5\%$ for $E_T^{min} = 25$ GeV. A comparable source of systematic uncertainty at that jet E_T threshold comes from the jet energy calibration.

The measurement of R_{10} is compared to NLO QCD predictions obtained by the DYRAD Monte Carlo [13], tailored to the experimental e and Jet definitions used at DØ, and by the experimental resolutions. Figure 6 shows the measured R_{10} distribution as a function of E_T^{min}, compared to the theoretical prediction. NLO QCD does underestimate the absolute value of the measurement by 4σ, independent of the threshold chosen for the jet E_T. Little variation is observed in the prediction when varying PDFs or the normalization and factorization scales.

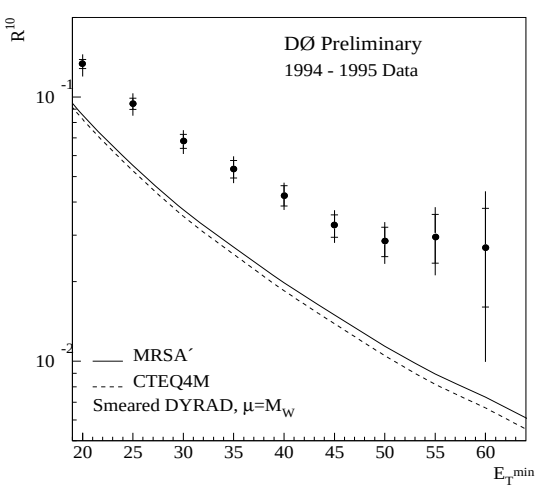

Figure 6. D0's $W + 1\ Jet$ to $W + 0\ Jet$ ratio as a function of jet E_T^{min}, compared to NLO QCD prediction by[13].

5. CONCLUSIONS

Using approximately 100 pb^{-1} of data from Run 1 at the Tevatron, the CDF and DØ collaborations make precise measurements of the vector boson production properties that test QCD predictions. The inclusive measurements show good agreement with the Standard Model predictions. CDF's measured $W+ \geq n\ Jets$ cross sections are a factor of 1.7 larger than the LO QCD prediction for $Q^2_{REN,FAC} = M^2(W) + p_T^2(W)$. DØ's measured $W + 1\ Jet$ to $W + 0\ Jet$ ratio is underestimated by NLO QCD by 4σ, independent of the threshold chosen for the jet E_T.

We are grateful to the DØ and CDF collaborations for discussions of their data.

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