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Electroweak Measurements from CDF and D0

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This paper highlights results from electroweak measurements recently obtained by the CDF and DØ collaborations in 1.8 TeV $p\bar{p}$ collisions. The W decay width was extracted from the measurement of W/Z cross section times leptonic branching ratios, and in a direct measurement from a fit of the high-mass tail of the transverse mass spectrum of the W system. Various limits on anomalous gauge boson couplings were obtained in studies of $W/Z+\gamma$ processes, single leptonic WW, WZ production and double leptonic WW production. Values for $\sigma B(W\gamma \to \ell\nu\gamma)$, $\sigma B(Z\gamma \to \ell^+\ell^-\gamma)$, and $\sigma(p\bar{p} \to WW+X)$ were measured. CDF also reports on the observation of an asymmetry in photon rapidity distributions as predicted by the Standard Model.

1 Introduction

Experiments at the CERN LEP e^+e^- collider have collected large samples of Z bosons and have measured its properties with great accuracy. On the other hand, large amounts of W bosons are presently available only at the Tevatron $p\bar{p}$ collider at Fermilab, which thus offers a unique opportunity to make precision measurements in electroweak physics and to test the Standard Model (SM) in the 1 TeV range.

During the 1992-93 Tevatron collider run ('Run 1a'), the CDF and DØ experiments recorded ≈ 20 pb^{-1} and ≈ 13 pb^{-1} of data, respectively.

In the following, a summary of electroweak results obtained by CDF and DØ by analyzing Run 1a data will be given. Topics are the measurements of the W width, vector boson self-couplings and cross sections. The W mass measurement is described in a parallel contribution to these proceedings by L. Nodulman.

In addition, recent, preliminary data from the ongoing Tevatron run ('Run 1b'), which started in late 1993, will be presented. Preliminary results are marked by a dagger † throughout this paper.

2 W, Z Identification

The W and Z boson selection criteria are similar in the various analyses presented in this paper. Both experiments require an isolated electron or muon with high transverse momentum. In W events, the missing transverse energy, $\not\!\!E_T$, must be greater than 20 GeV. Z events are defined by the occurence of a second lepton which—with the first lepton—forms an invariant mass close to the Z mass. Specific event quality cuts can be found in the references for each analysis.

3 Measurement of the Inclusive W and Z Cross Sections

From a precise measurement of the number of clean W/Z events and their backgrounds (multijets, tauonic W/Z decays, Z events misidentified as W bosons) in the Run 1a data samples, and a detailed study of efficiencies and detector acceptances, DØ and CDF extracted the inclusive cross sections $\sigma B(W \to \ell\nu)$ and $\sigma B(Z \to \ell^+\ell^-)$ in the electron and muon channels[1-2].

The results for the cross sections and their ratios, $R = \sigma B(W \to \ell\nu)/\sigma B(Z \to \ell^+\ell^-)$, are compared to the SM predictions in Tab. 1. The integrated luminosity, $\mathcal{L}$, of the electron (e) and muon (μ) data sets is for CDF 19.6 ± 0.7 pb^{-1} (e) and 18.8 ± 0.7 pb^{-1}(μ), and for DØ 12.8 ± 0.7 pb^{-1} (e) and 11.4 ± 0.6 pb^{-1}(μ). Additionally, we list preliminary DØ results from Run 1b ($\mathcal{L} = 25.1 \pm 1.4$ pb^{-1} (e) and 30.7 ± 1.7 pb^{-1}(μ)).

4 Measurement of the Width of the W Boson

The W width is determined indirectly through the measurement of the ratios of the W/Z production cross section times branching ratio into leptons[2], given by

$$R = \frac{\sigma B(W \to \ell\nu)}{\sigma B(Z \to \ell^+\ell^-)} = \frac{\sigma_W}{\sigma_Z}\frac{\Gamma(W \to \ell\nu)}{\Gamma(Z \to \ell^+\ell^-)}\frac{\Gamma(Z)}{\Gamma(W)}\,. \quad (1)$$

CDF uses electron data only; DØ makes use of the combined electron + muon decay channel.

The predicted ratio of the production cross sections for W and Z bosons in $p\bar{p}$ collisions, σ_W/σ_Z, is calculated[3] to be 3.33 ± 0.03. For the remaining quantities, CDF and DØ chose slightly different input parameters. CDF uses the individual LEP measurements of the

Table 1: Summary of inclusive W/Z cross section times branching ratios, in nb, and the corresponding ratios, R, in the electron (e) and muon (μ) channels. † Preliminary Results.

ℓ	σB (W $\rightarrow \ell\nu$)	σB (Z $\rightarrow \ell^+\ell^-$)	R
⋆⋆⋆ DØ Run 1a ⋆⋆⋆			
e	2.36±0.15	0.218±0.016	10.8±0.5
μ	2.09±0.26	0.178±0.031	$11.8^{+2.1}_{-1.8}$
⋆⋆⋆ DØ Run 1b ⋆⋆⋆			
e†	2.24±0.20	0.226±0.022	9.9±0.9
μ†	1.93±0.20	0.159±0.026	12.3±1.6
⋆⋆⋆ CDF Run 1a ⋆⋆⋆			
e	2.49±0.08	0.231±0.009	10.9±0.4
μ†	2.48±0.19	0.203±0.014	12.2±0.8
⋆⋆⋆ SM ⋆⋆⋆			
	2.42±0.12	0.226±0.010	10.7±0.7

Z widths , $(Z) = 2.492 \pm 0.007$ GeV and , $(Z \rightarrow e^+e^-) = 83.33 \pm 0.30$ MeV [4], whereas DØ uses the branching ratio B(Z→ $\ell^+\ell^-$) = , $(Z \rightarrow \ell^+\ell^-)/,(Z) = 3.367 \pm 0.006$, also measured at LEP[5]. The following branching ratios are obtained:

$$\frac{,(W \rightarrow \ell\nu)}{,(W)} = \begin{cases} 0.1094 \pm 0.0033 & \text{(CDF)} \\ 0.1102 \pm 0.0050 & \text{(DØ)} \\ 0.1084 \pm 0.0002 & \text{(SM)}, \end{cases}$$

ℓ = e (CDF), e + μ (DØ).

Using the result of the theoretical calculation[6] of the partial width, the total W decay width becomes

$$,(W) = \begin{cases} 2.064 \pm 0.085 \text{ GeV} & \text{(CDF)} \\ 2.044 \pm 0.092 \text{ GeV} & \text{(DØ)} \\ 2.067 \pm 0.021 \text{ GeV} & \text{(SM)} \end{cases}$$

The measurements agree extremely well with the SM predictions[7] and leave little room for exotic decay modes.

In a direct measurement of the W width , (W), CDF performed a binned log-likelihood fit of the W transverse mass spectrum in the region $M_T^W > 110$ GeV/c^2. Since P_T^W is sufficiently well known and the Breit-Wigner tail is dominant is this mass region, a precise measurement of , (W) is possible. CDF obtains[8]

$$,(W) = 2.11 \pm 0.32 \text{ GeV}.$$

Fig.1 compares various measurements of , (W).

5 Gauge Boson Pair Production

The study of tri-linear gauge boson couplings is an important test of the SM, where strong gauge cancellations are predicted to occur in $W\gamma$, WW and WZ, but not in $Z\gamma$ processes. Anomalous gauge boson couplings would destroy the gauge cancellations and allow ZZγ interactions, resulting in a higher diboson production cross section than predicted by the SM. Such a deviation would signal the presence of new physics at and beyond an energy scale Λ_{FF}, which is introduced as a cutoff parameter in order to avoid unitarity violations in the cross section calculation.

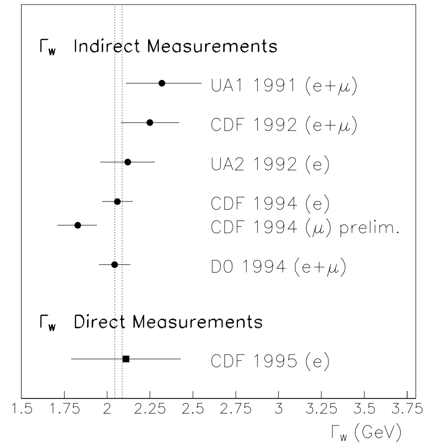

Figure 1: Comparison of the new CDF and DØ measurements of the W width to other results and to the Standard Model prediction (1σ band).

5.1 $W\gamma$ and $Z\gamma$ Production

To measure limits on anomalous weak boson - photon couplings the transverse energy (E_T) spectrum of photons with $E_T^\gamma >$ { 7 GeV (CDF), 10 GeV (DØ) } is compared to the SM prediction[9−10]. At large photon energies the sensitivity to anomalous couplings is particularly high.

The photons are required to be well isolated and separated from the charged W(Z) decay lepton(s). DØ (CDF) analyzed photons in the pseudo-rapidity range $|\eta| < 1.1$ and $1.5 < |\eta| < 2.5$ ($|\eta| < 1.1$).

In the combined electron and muon channel DØ measured 23 (6) $W\gamma$ ($Z\gamma$) candidates in the Run 1a data sample; CDF measures 109 (31) $W\gamma$ ($Z\gamma$) candidates in the combined Run 1a+b data sample (67 pb^{-1}) [11]. (A discussion of the CDF analysis of Run 1a data only can be found elsewhere[9−10].) Taking into account efficiencies, detector acceptances and backgrounds (mainly from jet fragmentation into isolated neutral mesons decaying into photons), CDF ($E_T^\gamma > 7$ GeV) and DØ ($E_T^\gamma > 10$ GeV) measure for a lepton photon separation $\Delta R_{\ell\gamma} > 0.7$[12]:

$$\sigma B(W\gamma \rightarrow \ell\nu\gamma) = \begin{cases} 20.7 \pm 3.0 \text{ pb}^{\dagger} & \text{(CDF)} \\ 18.6 \pm 2.9 \text{ pb} & \text{(SM)} \end{cases}$$

$$\sigma B(Z\gamma \rightarrow \ell^+\ell^-\gamma) = \begin{cases} 5.7 \pm 1.4 \text{ pb}^{\dagger} & \text{(CDF)} \\ 4.8 \pm 0.6 \text{ pb} & \text{(SM)} \end{cases}$$

$$\sigma(W\gamma \to \ell\nu\gamma) = \begin{cases} 138 \ {}^{+\,55}_{-\,43} \ \text{pb} & (\text{DØ}) \\ 112 \pm 10 \ \text{pb} & (\text{SM}) \end{cases}$$

The results compare well with the SM prediction. Due to the presence of gauge cancellations in $W\gamma$ processes, the ratio of $W\gamma$ to $Z\gamma$ cross sections is a factor of ≈ 3 times lower than the inclusive W to Z cross section ratio.

A log-likelihood fit of the background corrected E_T^γ spectra yields limits on the anomalous couplings. The following direct 95% CL limits on the $\mathcal{CP}$ conserving couplings were measured[a]:

$W\gamma$ production :	-1.8	$<$	$\Delta\kappa$	$<$	$2.0^\dagger$	(CDF)
	-1.6	$<$	$\Delta\kappa$	$<$	1.8	(DØ)
	-0.7	$<$	λ	$<$	$0.6^\dagger$	(CDF)
	-0.6	$<$	λ	$<$	0.6	(DØ)
$Z\gamma$ production :	-1.6	$<$	h_{30}^Z	$<$	$1.6^\dagger$	(CDF)
	-1.8	$<$	h_{30}^Z	$<$	1.8	(DØ)
	-0.4	$<$	h_{40}^Z	$<$	$0.4^\dagger$	(CDF)
	-0.5	$<$	h_{40}^Z	$<$	0.5	(DØ)

Results for $\mathcal{CP}$ violating couplings are the same to the precision quoted. A form factor scale $\Lambda_{FF} = 1.5$ TeV (0.5 TeV) for $W\gamma$ ($Z\gamma$) processes was assumed. This scale defines a lower limit for the energy region where the SM, in which all the above couplings must vanish, might not be valid anymore.

5.2 WW and WZ Production

The Single Leptonic Decay Channel

For weak diboson pairs the signature for non-SM couplings is an excess rate of bosons with high transverse momentum, P_T. CDF (DØ) searches Run 1a data for WW and WZ candidates consistent with a leptonic decay of one boson (a W boson) and a hadronic decay of the other[13−14].

W/Z + QCD jet background at high W/Z transverse momenta is strongly suppressed. CDF analyzes the P_T distribution of the dijet, P_T^{jj}, interpreted as hadronic W/Z decay; DØ analyzes the P_T spectrum of the electronic W decay, $P_T^{e\nu}$. Cutting at high P_T^{jj} or $P_T^{e\nu}$ eliminates not only background, but also the SM signal. However, sensitivity to anomalous couplings is retained.

CDF observed one candidate in the $\ell\nu jj$ and none in the $\ell\ell jj$ channel, after cutting at $P_T^{jj} > 130$ GeV/c (100 GeV/c) for leptonic W (Z) events. DØ measures one $WW, WZ \to e\nu jj$ candidate with $P_T^{e\nu} > 130$ GeV/c. These results are not indicative of non-SM couplings as the SM predicts 0.13 $WW, WZ \to \ell\nu jj$ and 0.02 $WZ \to \ell\ell jj$ events.

CDF extracted limits on anomalous couplings by calculating the probability for the number of observed WW and WZ candidates to fluctuate to the number of events predicted by the SM, including systematic uncertainties. These are conservative limits since no background subtraction was performed.

DØ performed a series of background subtracted fits to the P_T^W spectrum, with a P_T^W cut changed from 25 GeV/c to 130 GeV/c. In this analysis a detailed background study was necessary.

Assuming $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda \equiv \lambda_\gamma = \lambda_Z$, the following limits at 95% CL for $\Lambda_{FF} = 1.5$ TeV were measured [a]:

-0.9	$<$	$\Delta\kappa$	$<$	1.0	(CDF)
-0.9	$<$	$\Delta\kappa$	$<$	$1.1^\dagger$	(DØ)
-0.6	$<$	λ	$<$	0.7	(CDF)
-0.7	$<$	λ	$<$	$0.7^\dagger$	(DØ)

The Double Leptonic Decay Channel

CDF and DØ measured double leptonic WW decays using standard W selection criteria[15].

In 67 pb^{-1} data from Run 1a+b CDF measures 5 candidates †. Taking into account efficiencies, detector acceptances and backgrounds (1.23 ± 0.43 $t\bar{t}$, $b\bar{b}$, $Z \to \tau\tau$, Drell-Yan and misidentified events) the cross section becomes $\sigma(p\bar{p} \to WW + X) = 13.8^{+9.6}_{-7.9}$ pb †, in good comparison with the SM value of 9.5 pb.

In the DØ analysis of Run 1a data, one $ee\nu\nu$ passes all cuts. The background estimtate is 0.56 ± 0.13 and the SM prediction 0.47 ± 0.08 events. An upper cross section limit of 87 pb at 95% CL was extracted. A comparison with MC predicitions yields bounds on anomalous couplings[a]: $-2.6 < \Delta\kappa < 2.8$ and $-2.1 < \lambda < 2.1$ at 95% CL ($\Lambda_{FF} = 0.9$ TeV).

Comparison of the Limits

Fig. 2 a (b) compares 2-D anomalous coupling limit contours for a common form factor scale of 1.5 (0.5) TeV.

5.3 Recent Observations in $W\gamma$ and $Z\gamma$ Production †

The SM predicts a large forward-backward asymmetry for photons in $W\gamma$ events due to valence quark effects and the difference in the electric charges of the u and d quarks[16]. Such an asymmetry has not been observed previously.

$76 \pm 4\%$ of the $W\gamma$ events (electron + muon channel) with $1.1 < |\eta_\gamma| < 2.4$ are predicted to have a positive value for $Q_W \cdot \eta_\gamma$ and the W charge signed pseudorapidity difference distribution between the photon and the lepton, $Q_W \cdot \Delta\eta_{\gamma\ell}$. CDF measures after background subtraction $70 \pm 8\%$ for $Q_W \cdot \Delta\eta_{\gamma\ell}$ (Fig. 2 c) and $77 \pm 7\%$ for $Q_W \cdot \eta_\gamma$, confirming the predicted forward-backward asymmetry in $W\gamma$ production.

A notable event (not included in the above analyses[17]) is a rather clean $Z\gamma$ event with $M(e^+e) \sim$

[a] The convention is to set the remaining couplings to their SM value.

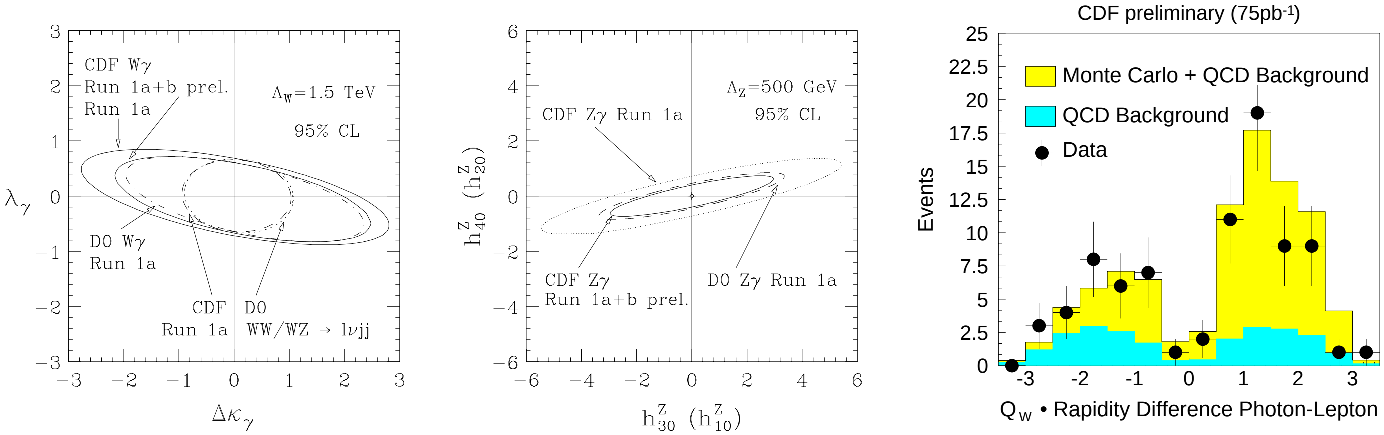

Figure 2: Vector boson self-interactions: Measured limit contours for a) $\mathcal{CP}$ conserving WWV (V = Z or γ) couplings, b) Z$Z\gamma$ couplings; c) Asymmetry in W charge-signed pseudo-rapidity difference distribution between the photon and the W decay lepton for $W\gamma$ production.

90 GeV/c^2 and an extremely high three body mass of $M(e^+e^-\gamma) \sim 420$ GeV/c^2 due to a photon with a remarkable E_T of 192 GeV[17].

6 Conclusions

We have discussed new CDF and DØ measurements of electroweak processes, most of which are not accessible at LEP. The high precision results are in excellent agreement with the Standard Model; no significant deviations have been found in the study of anomalous vector boson couplings. With an combined data set of > 120 pb^{-1} by the end of the Tevatron Run 1b, significant improvements are expected.

I would like to thank members of the CDF and DØ collaborations for helpful discussions.

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