W BOSON PHYSICS AT THE FERMILAB TEVATRON COLLIDER

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Recent results from the CDF and DØ Experiments at the Fermilab Tevatron Collider are presented for the \( W \) and \( Z \) boson production cross sections, the \( W \) boson width, rare \( W \) boson decays, trilinear gauge boson couplings, and the \( W \) boson mass.

I. INTRODUCTION

The CDF \( \dagger \) and DØ \( \ddagger \) detectors at the Fermilab Tevatron Collider collected data during 1992-96 corresponding to an integrated luminosity of about 130 pb\(^{-1}\) for each experiment. This “Run 1” was divided into three parts:

- Run 1A 1992–93 \( \sim 20 \) pb\(^{-1}\) of luminosity
- Run 1B 1994–95 \( \sim 90 \) pb\(^{-1}\)
- Run 1C 1995–96 \( \sim 20 \) pb\(^{-1}\)

The large number of \( W \) bosons detected (about 70,000 in the \( W \rightarrow e\nu \)) for each experiment in Run 1A+B) permits one to make precise measurements of its properties.

II. \( W \) AND \( Z \) PRODUCTION CROSS SECTIONS

The measurement of the production cross sections times leptonic branching ratios \( (\sigma \cdot B) \) for \( W \) and \( Z \) bosons can be used to test QCD predictions of the \( W \) and \( Z \) boson production. The \( W \) and \( Z \) bosons are detected via their leptonic decays: \( W \rightarrow e\nu, \mu\nu, \tau\nu \) and \( Z \rightarrow ee, \mu\mu \). For the \( e \) and \( \mu \) channels one selects \( W \) events with one isolated high transverse momentum lepton \( (p_T > 20 - 25 \text{ GeV/c}) \) and large missing transverse energy \( (E_T > 20 - 25 \text{ GeV}) \), and \( Z \) events with two isolated leptons with \( p_T > 20 - 25 \text{ GeV/c} \). The backgrounds are mainly due to QCD and cosmic rays, and are typically \( < 15\% \) for the \( W \) sample and \( < 5\% \) for the \( Z \) sample. Recent results for CDF \( \dagger \) and DØ are shown in Fig.1, and are compared to the \( O(\alpha_s^2) \) theoretical QCD prediction \( \dagger \). One sees that there is excellent agreement, providing an important verification of QCD.

\( \dagger \)Invited plenary talk at the XVIII International Conference on Physics in Collision, Frascati, Italy, June 17-19, 1998.

DØ has also measured \( W \) production cross sections by detecting \( W \rightarrow \tau\nu \). The \( \tau \) is identified through its hadronic decay products, which are highly boosted and form a very narrow hadronic jet in the DØ calorimeter. Thus one selects events with an isolated, narrow jet with \( E_T > 25 \text{ GeV} \), and \( E_T > 25 \text{ GeV} \). The \( \text{Profile} \) variable, defined as the sum of the two highest \( E_T \) towers divided by the \( E_T \) of the jet, exploits the fine segmentation and good energy resolution of the DØ calorimeters to provide a powerful discrimination against QCD backgrounds. \( W \rightarrow \tau\nu \) hadronic decays produce very narrow jets, leading to high values of \( \text{Profile} \), and QCD jets yield wider jets, and therefore lower values of \( \text{Profile} \). Events are selected with \( \text{Profile} > 0.55 \). In a data sample of 17 pb\(^{-1}\) DØ finds 1,202 candidate events, with a background of 222 \( \pm \) 16 events. The acceptance \( \times \) efficiency is 3.8\%. The preliminary cross section times branching ratio that DØ obtains is

\[
\sigma_W \cdot B(W \rightarrow \tau\nu) = 2.38 \pm 0.09 \pm 0.10 \pm 0.20 \text{ nb},
\]

where the errors are statistical, systematic and luminosity, respectively. Comparing this result with DØ’s published value \( \ddagger \) for \( \sigma_W \cdot B(W \rightarrow e\nu) \) measures the ratio of the tau and electron electroweak charged current cou-
plings to the $W$ boson:

$$g_W^W / g_\tau^W = 1.004 \pm 0.019 \text{(stat)} \pm 0.026 \text{(syst)}.$$  

This result, shown in Fig. 2 with the results of other experiments, is in excellent agreement with $e - \tau$ universality.

### III. W BOSON WIDTH

#### A. Indirect Measurement of $\Gamma(W)$

One can indirectly measure the $W$ boson width from the ratio of the $W$ and $Z$ production cross sections:

$$R \equiv \frac{\sigma_W \cdot B(W \to l\nu)}{\sigma_Z \cdot B(Z \to ll)} = \left[ \frac{\sigma_W}{\sigma_Z} \cdot \frac{1}{B(Z \to ll)} \right] \frac{\Gamma(W \to l\nu)}{\Gamma(W)}$$  \hspace{1cm} (1)$$

where $l = e$ or $\mu$, $\sigma_W$ and $\sigma_Z$ are the inclusive cross sections for $W$ and $Z$ boson production in $p\bar{p}$ collisions, $B(W \to l\nu) = \Gamma(W \to l\nu)/\Gamma(W)$ is the leptonic branching ratio of the $W$ boson, and $B(Z \to ll)$ is the leptonic branching ratio of the $Z$ boson. Many common sources of error cancel in $R$, including the uncertainty in the luminosity and some of the errors in the acceptance and efficiency. We extract the $W$ boson total width, $\Gamma(W)$, from Eq. 1 by using the measured value of $R$, a theoretical calculation of $\sigma_W/\sigma_Z$, the precise measurement of $B(Z \to ll)$ from LEP, and a theoretical calculation of $\Gamma(W \to l\nu)$. Figure 3 summarizes $\Gamma(W)$ measurements from various experiments, along with the Standard Model prediction. The agreement of the experimental values with the theoretical prediction can be used to

#### B. Direct Measurement of $\Gamma(W)$

CDF has made a direct measurement of $\Gamma(W)$ from the $W$ boson transverse mass lineshape for $W \to e\nu$ events:

$$M_T^2 = 2E_T^l E_T^\nu (1 - \cos\phi_{l\nu})$$  \hspace{1cm} (2)$$

A larger value of $\Gamma(W)$ increases the high transverse mass tail. CDF determines $\Gamma(W)$ from a binned likelihood fit to the $M_T$ spectrum in the region $M_T > 110 \text{ GeV/c}^2$, where the Breit-Wigner line shape dominates over the Gaussian resolution of the detector. The CDF $M_T$ spectrum and fit are shown in Fig. 3, and the preliminary value from this analysis of Run 1B data is:

$$\Gamma(W) = 2.19^{+0.17}_{-0.16}(\text{stat}) \pm 0.09(\text{syst}) \text{ GeV}.$$  

This result is in good agreement with the indirect measurements and the SM prediction.

### IV. RARE W DECAYS

#### A. $W \to \pi\gamma$

The ratio of the partial widths of the decays $W \to \pi\gamma$ to $W \to e\nu$ is predicted to be $\Gamma(W \to \pi\gamma)/\Gamma(W \to e\nu)$.
$e\nu \simeq 3 \times 10^{-8}$. CDF has the best previous experimental limit on this ratio of $2.0 \times 10^{-3}$. CDF now has new results on $W \to \pi\gamma$ based on 83 pb$^{-1}$ of data taken in Run 1B (1994-95). They chose events with one isolated photon with $p_T > 23$ GeV/c and one jet consistent with a single, isolated charged pion with $p_T > 15$ GeV/c, separated by $\Delta \phi > 1.5$ radians, and no other jets with $E_T > 15$ GeV. The $\pi\gamma$ masses of the 28 events that result from these cuts are shown in Fig. 5, along with the estimate of the background (which is due mainly to QCD direct photons). There are 3 events in the $W$ mass region, with an estimated background of 5.2 $\pm$ 1.5 events. The acceptance $\times$ efficiency is 3.8%. Thus CDF finds at the 95% CL that $\sigma_W \cdot B(W \to \pi\gamma) < 1.7$ pb, and that $\Gamma(W \to \pi\gamma)/\Gamma(W \to e\nu) < 7 \times 10^{-4}$. This limit is a factor of three times better than their previous limit.

B. $W \to D_s\gamma$

The theoretical prediction for the ratio of the partial widths $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu)$ is $1 \times 10^{-7}$, which is three times larger than the relative branching fraction for the decay $W \to \pi\gamma$. However, the multitude of $D_s$ decay modes and the choice of particular modes for experimental identification makes the experimental reach smaller in the $W \to D_s\gamma$ case. CDF has put a limit on this relative branching fraction using 82 pb$^{-1}$ of data from Run 1B (1994-95). They selected events with one isolated photon with $p_T > 22$ GeV/c, and one isolated $D_s$ candidate with $p_T > 22$ GeV/c. The $D_s$ mesons are identified via the decay modes $D_s \to \phi\pi$ (with $\phi \to K\pi$), and $D_s \to K^{*0}K$ (with $K^{*0} \to K\pi$). They find 4 events with a $D_s\gamma$ mass consistent with the $W$, with an estimated background of 4 events (mainly due to QCD direct photons). The acceptance $\times$ efficiency is 6.9%. Thus CDF finds at the 95% CL that $\sigma_W \cdot B(W \to D_s\gamma) < 27.4$ pb, and that $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu) < 1.1 \times 10^{-2}$. This is the first measurement of this quantity.

V. TRILINEAR GAUGE BOSON COUPLINGS

The Standard Model (SM) predicts the existence of gauge boson self-interactions, and makes unique predictions for the strength of these trilinear gauge boson couplings. Measurements of these couplings test the SM, and any significant deviation from SM predictions would be compelling evidence for new physics. As is seen in Fig. 6, the direct measurement of these trilinear couplings ($WW\gamma$, $WWZ$, $ZZ\gamma$, and $Z\gamma\gamma$) is possible by measuring diboson production at the Tevatron.

![Fig. 5. Distribution of the $\pi\gamma$ mass for the 28 CDF $W \to \pi\gamma$ candidates. The shaded band shows the one sigma uncertainty in the background expectation value.](image)

![Fig. 6. Measurement of the trilinear gauge boson couplings $WW\gamma$, $WWZ$, $ZZ\gamma$, and $Z\gamma\gamma$ using diboson events.](image)
a form factor \((1 + \hat{s}/\Lambda^2)^n\), where \(n=2\) for WWV couplings, 3 for \(h_{30}\), and 4 for \(h_{40}\), \(\hat{s}\) is the square of the sub process center-of-mass energy, and \(\Lambda\) is the form factor scale. Anomalous (i.e. non Standard Model) values of the coupling parameters increase the diboson production cross section and enhance the \(p_T\) spectrum of the gauge bosons for large values of \(p_T\).

### A. \(W\gamma\) Production

The detection of \(W\gamma\) events enables one to measure the \(\lambda_\gamma\) and \(\Delta \kappa_\gamma\) parameters that characterize \(WW\gamma\) couplings. One uses the leptonic decays of the \(W\), and selects events with an isolated high \(p_T\) muon or electron, and with large \(E_T\). The event must also have an isolated photon with \(E_T > 10\) GeV (DØ) or 7 GeV (CDF). The main background is \(W\) plus \(\pi\) production. These events are selected by requiring two isolated leptons of 37.1 pb. In a 97 pb\(^{-1}\) sample DØ finds 5 events, with a background of 3.1 ± 0.4 events, and sets a 95% CL upper limit on \(\sigma_{WW}\) of 37.1 pb. In an 108 pb\(^{-1}\) sample CDF also finds 5 events, but with a lower background of 1.2 ± 0.3 events, and thus measures \(\sigma_{WW} = 10.2^{+6.3}_{-5.1} \pm 1.6\) pb. The SM prediction is \(\sigma_{WW} = 9.5\pm1.0\) pb, so there is no evidence for anomalous WW production. To get limits on the anomalous coupling parameters, CDF fits to the total number of events. DØ fits to the lepton \(p_T\) spectrum, which gives significantly better limits. DØ finds, for \(\Lambda = 1.5\) TeV, and assuming \(\Delta \kappa_Z = \Delta \kappa_\gamma\), and \(\kappa_Z = \kappa_\gamma = -0.62 < \Delta \kappa < 0.77\) (for \(\lambda = 0\)), and \(-0.53 < \lambda < 0.56\) (for \(\Delta \kappa = 0\)).

### B. \(WW \rightarrow l\nu l\nu\) \((l = e, \mu)\)

These events are selected by requiring two isolated leptons with \(p_T > 15 - 25\) GeV/c, and \(E_T > 20 - 25\) GeV. The main backgrounds are due to \(t\bar{t}, Z \rightarrow \tau\tau\), and Drell-Yan production. In a 97 pb\(^{-1}\) sample DØ finds 5 events, with a background of 3.1 ± 0.4 events, and sets a 95% CL upper limit on \(\sigma_{WW}\) of 37.1 pb. In a 108 pb\(^{-1}\) sample CDF also finds 5 events, but with a lower background of 1.2 ± 0.3 events, and thus measures \(\sigma_{WW} = 10.2^{+6.3}_{-5.1} \pm 1.6\) pb. The SM prediction is \(\sigma_{WW} = 9.5\pm1.0\) pb, so there is no evidence for anomalous WW production. To get limits on the anomalous coupling parameters, CDF fits to the total number of events. DØ fits to the lepton \(p_T\) spectrum, which gives significantly better limits. DØ finds, for \(\Lambda = 1.5\) TeV, and assuming \(\Delta \kappa_Z = \Delta \kappa_\gamma\), and \(\kappa_Z = \kappa_\gamma = -0.62 < \Delta \kappa < 0.77\) (for \(\lambda = 0\)), and \(-0.53 < \lambda < 0.56\) (for \(\Delta \kappa = 0\)).

### C. \(WW, WZ \rightarrow l\nu jj, lljj\) \((l = e, \mu)\)

These events are selected by requiring one isolated lepton with \(p_T > 20 - 25\) GeV/c, two or more jets with \(E_T > 20 - 30\) GeV which have an invariant mass consistent with a \(W\) or a \(Z\), and \(E_T > 20 - 25\) GeV (or a second high \(p_T\) lepton for the \(lljj\) events). The background from \(W\)+jets is large in this channel. CDF uses events with \(p_T(jj) > 200\) GeV/c to get anomalous coupling limits, and DØ uses a binned likelihood fit to the \(p_T(W)\) spectrum to get them. The limits on the anomalous couplings \(\Delta \kappa\) and \(\lambda\) obtained by each experiment are similar, and are about a factor of 1.4 tighter than those from the \(WW \rightarrow l\nu l\nu\) channel. The coupling \(\lambda_Z = \kappa_Z = 0\) is excluded at > 99% CL by both ex-
D. Z\gamma Production

DØ [17] and CDF [12] have each measured Z(ee)γ and Z(\mu\mu)γ production. DØ (CDF) finds 35 (33) events in 105 (67) pb\(^{-1}\), with a background of 5.9 (1.4) events. The measurements agree with Standard Model expectations, and limits on the anomalous coupling parameters are found using a binned maximum likelihood fit to the photon \(E_T\) spectrum. The results are the outer two ellipses in Fig.8.

DØ has also measured \(Z(\nu\nu)\gamma\) production. The sensitivity to anomalous couplings is much higher in the \(Z(\nu\nu)\gamma\) channel than in the \(Z(ll)\gamma\) channel due to a higher branching ratio and the absence of diluting radiative Z decay events. But the measurement of \(Z(\nu\nu)\gamma\) production is very challenging at a hadron collider because of the extremely high background (due to muon bremsstrahlung, \(W\rightarrow e\nu\), jet-jet and jet-\gamma production, etc.). Features of DØ that enable them to do this measurement are:

Hermeticity: The excellent hermeticity of the DØ calorimeter results in a small tail in the missing \(E_T\) resolution, and reduces the QCD background.

Hit Counting: Because of the high hit efficiency of the tracking chamber, one can count hit wires to help eliminate background due to \(W\rightarrow e\nu\), even if the track for the electron is not reconstructed.

Photon “Tracking” in the Calorimeter: Because of the fine longitudinal and transverse segmentation in the DØ electromagnetic calorimeter, one can determine the direction of the photon and determine if it came from the primary vertex, and thus reduce the muon bremsstrahlung background from cosmic rays and beam halo.

Muon “Tracking” in the Calorimeter: Because one can detect minimum ionizing particles in the DØ calorimeter, one can reduce the muon bremsstrahlung background from cosmic rays and beam halo by searching for a line of minimum ionizing hits in the calorimeter.

In the \(Z(\nu\nu)\gamma\) channel DØ finds 4 events, with a background of 5.8 ± 1.0 events, for 13 pb\(^{-1}\). One expects 1.8 ± 0.2 events from the Standard Model. Anomalous coupling limits are found using a binned maximum likelihood fit to the \(E_T(\gamma)\) spectrum, and are shown as the inner ellipses in Fig.8. Combining the results from the \(Z(ll)\gamma\) and \(Z(\nu\nu)\gamma\) channels, DØ [17] finds, for \(\Lambda = 750\) GeV:

\[ |\hat{h}_{30}^{Z\gamma}| < 0.37 \quad \text{and} \quad |\hat{h}_{40}^{Z\gamma}| < 0.05 \]

These are the most stringent direct limits on anomalous couplings from any experiment.

E. DØ Combined Analysis of WW\gamma and WWZ Couplings

DØ has performed [19] a simultaneous fit to the photon \(p_T\) spectrum in the \(W\gamma\) data, the lepton \(p_T\) distribution in the WW dilepton data, and the W \(p_T\) distribution in the WW/WZ \(\rightarrow e\nu jj\) data. The limits on the WW\gamma and WWZ anomalous coupling parameters are extracted from the fit taking correlations properly into account, and are shown in Fig.8 assuming identical WW\gamma and WWZ couplings. The 95% CL limits, for \(\Lambda = 2.0\) TeV, are:

\[ -0.30 < \Delta \kappa < 0.43 \quad \text{(for} \lambda = 0) \]
\[ -0.20 < \lambda < 0.20 \quad \text{(for} \Delta \kappa = 0) \]

The DØ simultaneous fit has also been done using the alternative parameterization of the anomalous couplings used by the LEP groups: \(\alpha_{B\phi}, \alpha_{W\phi},\) and \(\alpha_W\). The resulting limits are listed in Table I. Also listed are the limits on the anomalous coupling parameters from combining [20] the DØ and LEP results. No anomalous diboson production has been seen at either the Tevatron or LEP, and stringent limits have been set on the anomalous coupling parameters.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
 & DØ & LEP & DØ + LEP \\
\hline
\(\alpha_{B\phi}\) & -0.77, 0.58 & -0.44, 0.95 & -0.42, 0.43 \\
\(\alpha_{W\phi}\) & -0.22, 0.44 & -0.12, 0.13 & -0.14, 0.10 \\
\(\alpha_W\) & -0.20, 0.20 & -0.21, 0.27 & -0.18, 0.13 \\
\hline
\end{tabular}
\caption{DØ limits on anomalous couplings \(\alpha_{B\phi},\alpha_{W\phi},\) and \(\alpha_W\) at the 95% CL from a simultaneous fit to the \(W\gamma,WW\rightarrow e\nu e\nu,\) and \(WW/WZ\rightarrow e\nu jj\) data. Also shown are the LEP limits, and the LEP + DØ combined limits.}
\end{table}
The charged lepton energy measurement and the hadronic recoil measurement in order to correctly model $M_T$ in the Monte Carlo. These are briefly discussed below.

The most recent Tevatron measurements of $M_W$, using the Run 1B (1994-95) data, are DØ’s published result [21] using the $W \rightarrow e\nu$ channel, and CDF’s preliminary result [22] using the $W \rightarrow \mu\nu$ channel. The experiments select events with an isolated, high quality lepton in the central region with $p_T > 25$ GeV/c, $E_T > 25$ GeV, and hadronic recoil $< 15 - 20$ GeV. This results in a sample of 28K $W \rightarrow e\nu$ events for DØ, and 21K $W \rightarrow \mu\nu$ events for CDF.

The DØ electromagnetic (EM) calorimeter energy scale is initially set by test beam measurements, and then finally determined from collider data. The observed EM energy is parameterized as $E_{\text{obs}} = \alpha E_{\text{true}} + \delta$, and the parameters $\alpha$ and $\delta$ are determined from $Z \rightarrow ee, \pi^0 \rightarrow \gamma\gamma$, and $J/\psi \rightarrow ee$ collider data, as shown in Fig.[10]. DØ finds that $\alpha = 0.9533 \pm 0.0008$ and $\delta = -0.16^{+0.21}_{-0.16}$ GeV, including systematic errors from underlying event corrections and nonlinearity at low $E_T$. The uncertainty on $\alpha$ ($\delta$) results in an error on $M_W$ of 65 (20) MeV. DØ uses its $Z \rightarrow ee$ sample to measure the constant term in the EM energy resolution, and the measured uncertainty in the energy resolution results in an error on $M_W$ of 20 MeV.

The momentum scale of the CDF central tracker is determined by normalizing the observed $J/\psi \rightarrow \mu\mu$ peak to the world average, as is seen in Fig.[11]. They find $\Delta M_{J/\psi} = 0.7 \pm 1.5$ MeV. The uncertainty on $\Delta M_{J/\psi}$ results in an error on $M_W$ of 40 MeV. CDF uses its $Z \rightarrow e\nu$ sample to measure the momentum resolution, and the measured uncertainty in the momentum resolution results in an error on $M_W$ of 25 MeV.

Both DØ and CDF use the transverse energy balance of the $Z$ boson and the hadronic recoil products in $p\bar{p} \rightarrow Z + X$ events to determine the hadronic recoil energy scale and resolution. DØ uses $Z \rightarrow e\nu$ events, and CDF uses $Z \rightarrow \mu\nu$ events. Thus the hadronic recoil scale is measured relative to the lepton energy scale. The error on $M_W$ due to the uncertainty in the hadron recoil scale and resolution, and the uncertainty on the recoil model, is 35 (90) MeV for DØ (CDF).

The fits to the $M_T$ distributions are shown in Fig.[12] for DØ and in Fig.[13] for CDF. The results for these Run
1B measurements are:

DO 1B : $M_W = 80.440 \pm 0.095 \pm 0.065 \text{ GeV/c}^2$

CDF 1B : $M_W = 80.430 \pm 0.100 \pm 0.120 \text{ GeV/c}^2$

where the first error is statistical, and the second is systematic. Table I summarizes the sources of uncertainty in each of the measurements. Combining these results with those of DO [23] and CDF [24] from Run 1A gives:

DO 1A + B : $M_W = 80.430 \pm 0.110 \text{ GeV/c}^2$

CDF 1A + B : $M_W = 80.375 \pm 0.120 \text{ GeV/c}^2$

Combining these results with those of UA2 [25] gives a Hadron Collider Average of:

Hadron Collider Average : $M_W = 80.400 \pm 0.090 \text{ GeV/c}^2$

Combining the Hadron Collider Average with the LEP2 result [26] of $M_W = 80.350 \pm 0.090 \text{ GeV/c}^2$ presented at this conference gives a World Average of direct $M_W$ measurements:

Direct World Average : $M_W = 80.375 \pm 0.064 \text{ GeV/c}^2$

These direct $M_W$ measurements are summarized in Fig. 14. In Fig. 15 $M_W$ is plotted versus $M_{top}$. The point

\[
\chi^2/\text{dof} = 79.560 \text{ KS Prob = 25%}
\]

FIG. 12. Transverse mass distribution of $W \rightarrow e\nu$ events from the DØ Run 1B data, with the best fit. The shaded distribution is the background.

\[
\chi^2/\text{dof} = 158/139 \ (50 < M_T < 120) \chi^2/\text{dof} = 62/69 \ (65 < M_T < 100) \ M_w = 80.430 \pm 0.100 \text{ (stat) GeV}
\]

FIG. 13. Transverse mass distribution of $W \rightarrow \mu\nu$ events from the CDF Run 1B data, with the best fit. The shaded distribution is the background.

| Table II. Summary of Errors on $M_W$ (in MeV/c$^2$) for the Run 1B Measurements. |
|-----------------------------------------------|
|                                | CDF | DØ |
| Statistical                    |     |     |
| W sample                       | 100 | 70  |
| Z sample (e energy scale)      | –   | 65  |
| Total Statistical              | 100 | 95  |
| Systematic                     |     |     |
| Muon momentum scale            | 40  | –   |
| Lepton energy resolution       | 25  | 20  |
| Calorimeter linearity          | –   | 20  |
| Recoil modeling                | 90  | 35  |
| W production model             | 55  | 30  |
| Backgrounds                    | 25  | 10  |
| Lepton angle calibration       | –   | 30  |
| Fitting                        | 10  | –   |
| Miscellaneous                  | 15  | 10  |
| Total Systematic               | 120 | 65  |
| Total Uncertainty              | 155 | 115 |

\[
80.360 \pm 0.370 \text{ UA2 (W \rightarrow ev)}
\]

\[
80.410 \pm 0.180 \text{ CDF(Run 1A, W \rightarrow e\mu\nu)}
\]

\[
80.430 \pm 0.155 \text{ CDF(Run 1B*, W \rightarrow \mu\nu)}
\]

\[
80.375 \pm 0.120 \text{ CDF combined*}
\]

\[
80.350 \pm 0.270 \text{ D0(Run 1A, W \rightarrow ev)}
\]

\[
80.440 \pm 0.115 \text{ D0(Run 1B, W \rightarrow ev)}
\]

\[
80.430 \pm 0.110 \text{ D0 combined}
\]

\[
80.400 \pm 0.090 \text{ Hadron Collider Average* (50 MeV Common Error)}
\]

\[
80.350 \pm 0.090 \text{ LEP II* (ee \rightarrow WW)}
\]

\[
80.375 \pm 0.064 \text{ World Average}
\]

\[
* : \text{ Preliminary}
\]

FIG. 14. Summary of direct $W$ mass measurements.
FIG. 15. $M_W$ vs $M_{\text{top}}$. The point is the combined result from direct measurements. Also shown are the allowed regions from LEP1/SLC and NuTeV, the prediction of the minimal supersymmetric model (MSSM), and the Standard Model predictions for Higgs masses from 100 – 1000 GeV/c².

is the Direct World Average, with $M_{\text{top}}$ taken from DØ and CDF measurements. Also shown are the indirect LEP1/SLC and NuTeV [27] measurements, the prediction of the Minimal SuperSymmetric Model (assuming no SUSY particles have masses low enough to be discovered at LEP2), and the Standard Model predictions for Higgs masses from 100 – 1000 GeV/c².

Most of the systematic errors in the Tevatron $M_W$ measurements are still statistics limited, since they are determined with collider data. Thus we expect improvements in both the short and long term future. With the Run 1 data, DØ is using its forward electrons, and expects to have a final $\Delta M_W$ of less than 100 MeV. CDF is finalizing its muon results with smaller errors, and also using Run 1B electrons, and expects to have a final $\Delta M_W$ of about 90 MeV. Thus one expects a final Tevatron Run 1 $\Delta M_W$ of about 75 MeV. Run 2 at the Tevatron Collider, scheduled to begin in April 2000, will have 20 times more integrated luminosity than Run 1. DØ is upgrading its tracking system, and adding new preshower detectors and a new solenoid (which will enable them to also use muons to measure $M_W$). CDF is upgrading its tracking chambers, and will have a new forward calorimeter and extended muon coverage. It is expected that each experiment will be able to measure the $W$ boson mass to about 40 MeV.

VII. CONCLUSION

The $W$ boson mass has been measured at the Tevatron to a precision of 0.11%. Its value is consistent with the direct LEP2 measurement, the indirect LEP1/SLC and NuTeV measurements, and the Standard Model. The DØ and CDF measurements of diboson production agree with the Standard Model, and stringent limits have been set on trilinear gauge boson anomalous couplings. Measurements have been made of the $W$ and $Z$ production cross sections, the $W$ boson width, and rare $W$ decays, and no disagreement with the Standard Model has been found.

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