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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 [1] and DØ [2] 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 ~20 pb^{-1} of luminosity
Run 1B 1994–95 ~90 pb^{-1}
Run 1C 1995–96 ~20 pb^{-1}

The large number of W bosons detected (about 70,000 in the $W \to e\nu$ channel by 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 W and Z boson production. The W and Z bosons are detected via their leptonic decays: $W \to e\nu, \mu\nu, \tau\nu$ and $Z \to ee, \mu\mu$. For the e and μ channels one selects W events with one isolated high transverse momentum lepton ($p_T > 20-25$ GeV/c) and large missing transverse energy ($\not{E}_T > 20-25$ GeV), and Z events with two isolated leptons with $p_T > 20-25$ 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 [3] and DØ are shown in Fig.1, and are compared to the $\mathcal{O}(\alpha_s^2)$ theoretical QCD prediction [4]. One sees that there is excellent agreement, providing an important verification of QCD.

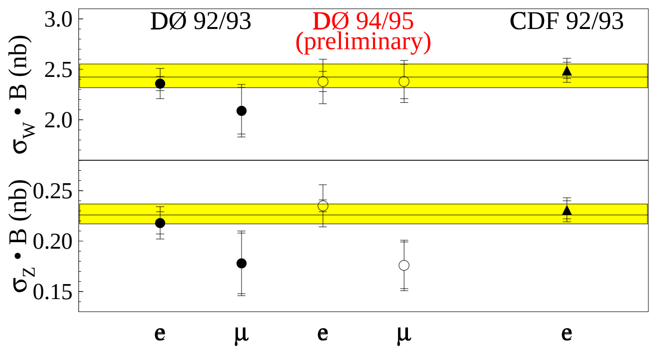

FIG. 1. *$\sigma \cdot B$ for inclusive W and Z production. The shaded bands are the $\mathcal{O}(\alpha_s^2)$ theoretical QCD prediction.*

DØ has also measured W production cross sections by detecting $W \to \tau\nu$. The τ 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 $E_T > 25$ GeV, and $\not{E}_T > 25$ GeV. The *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. $W \to \tau\nu$ hadronic decays produce very narrow jets, leading to high values of *Profile*, and QCD jets yield wider jets, and therefore lower values of *Profile*. Events are selected with *Profile* > 0.55. In a data sample of 17 pb^{-1} DØ finds 1,202 candidate events, with a background of 222 ± 16 events. The acceptance $\times$ efficiency is 3.8%. The preliminary cross section times branching ratio that DØ obtains is

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

where the errors are statistical, systematic and luminosity, respectively. Comparing this result with DØ's published value [5] for $\sigma_W \cdot B(W \to e\nu)$ measures the ratio of the tau and electron electroweak charged current cou-

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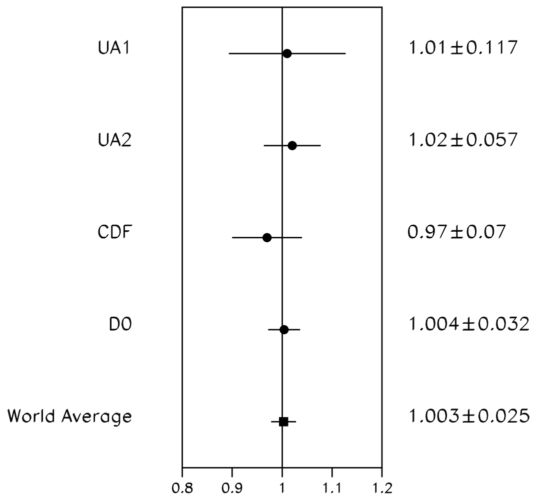

FIG. 2. *g_τ^W/g_e^W from various experiments.*

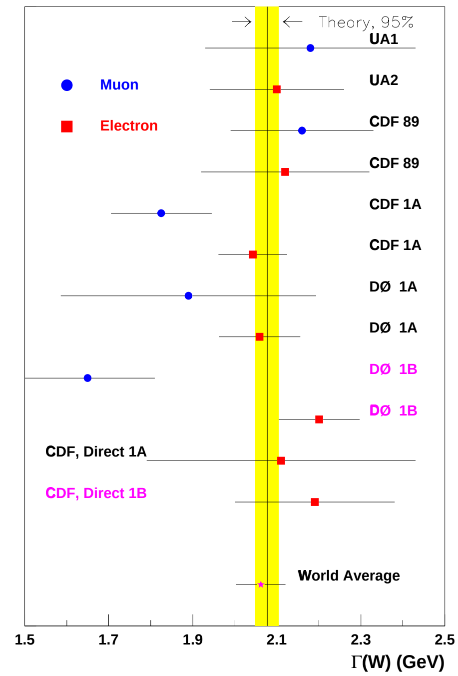

FIG. 3. *Summary of W width measurements and comparison with the Standard Model prediction.*

plings to the W boson:

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

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:

$$\begin{aligned} R &\equiv \frac{\sigma_W \cdot B(W \to l\nu)}{\sigma_Z \cdot B(Z \to ll)} \\ &= \left[\frac{\sigma_W}{\sigma_Z}\right] \cdot \frac{1}{B(Z \to ll)} \cdot \frac{\Gamma(W \to l\nu)}{\Gamma(W)} \end{aligned} \quad (1)$$

where $l = e$ or μ, σ_W and σ_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 σ_W/σ_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 set limits [5] on unexpected decay modes of the W boson, such as W decays into supersymmetric charginos and neutralinos, or into heavy quarks.

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:

$$M_T^2 = 2E_T^l E_T^\nu (1 - cos\phi^{l\nu}) \quad (2)$$

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 $M_T > 110$ 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.4, and the preliminary value from this analysis of Run 1B data is:

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

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 [6] to be $\Gamma(W \to \pi\gamma)/\Gamma(W \to$

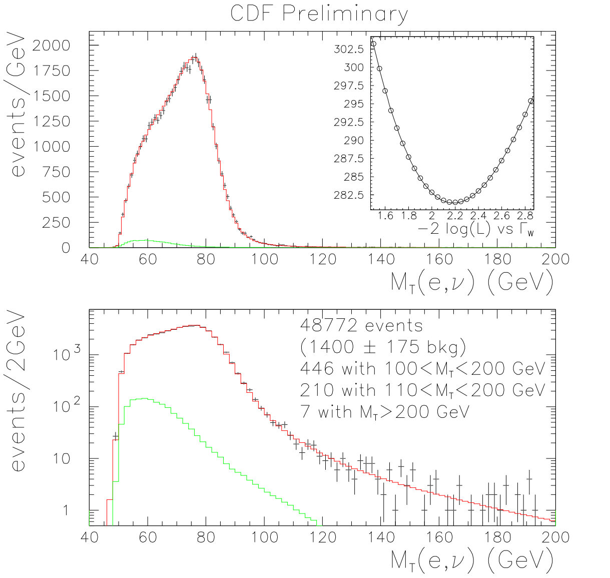

FIG. 4. *CDF M_T distribution for $W \to e\nu$ events, with the best fit for Γ_W overlayed. The size and shape of the background are also shown.*

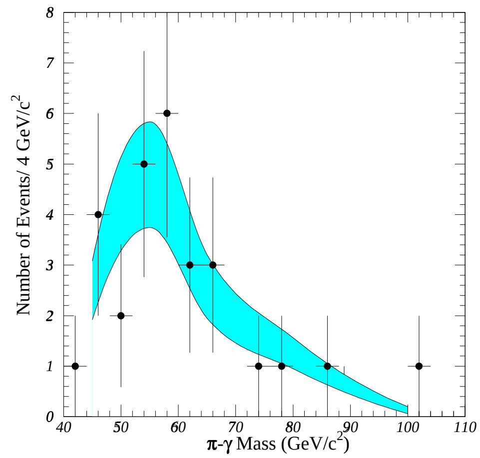

FIG. 5. *Distribution of the $\pi - \gamma$ mass for the 28 CDF $W \to \pi\gamma$ candidates. The shaded band shows the one sigma uncertainty in the background expectation value.*

$e\nu) \simeq 3 \times 10^{-8}$. CDF [7] has the best previous experimental limit on this ratio of 2.0×10^{-3}. CDF now has new results [8] 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 ± 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 [6] for the ratio of the partial widths $\Gamma(W \to D_s\gamma)/\Gamma(W \to e\nu)$ is 1×10^{-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 [9] on this relative branching fraction using 82 pb^{-1} of data from Run 1B (1994-95). They select 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 $\phi \to KK$), 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 [10].

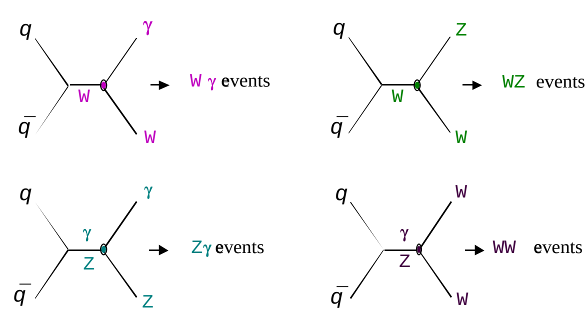

FIG. 6. *Measurement of the trilinear gauge boson couplings $WW\gamma$, WWZ, $ZZ\gamma$, and $Z\gamma\gamma$ using diboson events.*

WWV ($V = \gamma$ or Z) couplings are characterized by the parameters $\Delta\kappa_V (\equiv \kappa_V - 1)$ and λ_V, which are equal to zero in the SM. $ZV\gamma$ ($V = \gamma$ or Z) couplings are characterized by h_{30}^V and h_{40}^V, which are also zero in the SM. To obey unitarity, all couplings are multiplied by

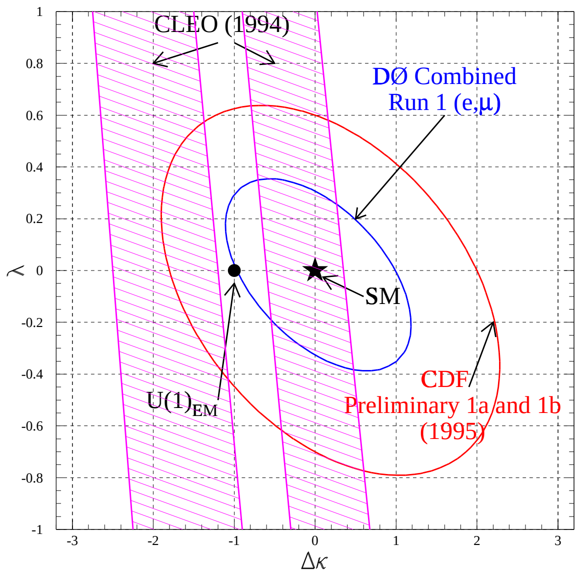

FIG. 7. *Contour limits on anomalous $WW\gamma$ couplings, from $W\gamma$ events.*

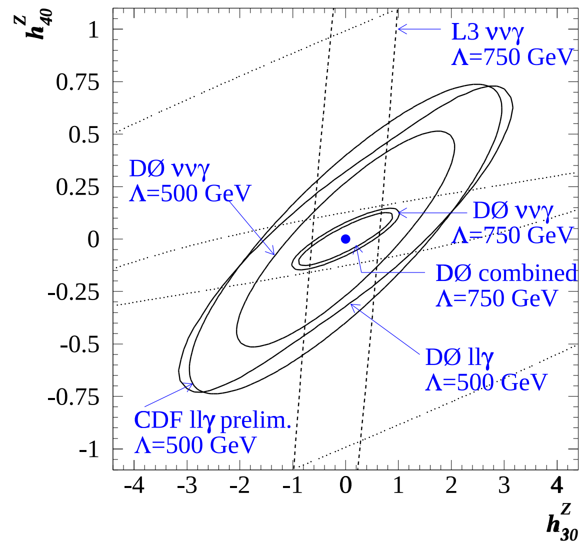

FIG. 8. *Contour limits on anomalous $ZZ\gamma$ couplings, from $Z\gamma$ events.*

a form factor $(1+\hat{s}/\Lambda^2)^n$, where n=2 for WWV couplings, 3 for h_{30}^V, and 4 for h_{40}^V, $\hat{s}$ is the square of the sub process center-of-mass energy, and Λ 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 λ_γ 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 $\not{E}_T$. The event must also have an isolated photon with $E_T > 10$ GeV (DØ) or 7 GeV (CDF). The main background is W+jets, where the jet fragments into a π^0, and $\pi^0 \to \gamma\gamma$. From the Run 1B data set, DØ [11] finds 127 candidate events with 93 pb^{-1}, and CDF [12] finds 109 events with 67 pb^{-1}. The anomalous coupling parameters are determined from a binned likelihood fit to the $p_T(\gamma)$ spectrum, and are shown in Fig.7. The DØ limits at 95% CL, for $\Lambda = 1.5$ TeV, are $-0.93 < \Delta\kappa_\gamma < 0.94$ (for $\lambda_\gamma = 0$), and $-0.31 < \lambda_\gamma < 0.29$ (for $\Delta\kappa_\gamma = 0$). These limits are independent of the WWZ vertex, unlike the limits obtained from WW production. From Fig.7 one sees that the DØ results exclude the coupling $\lambda_\gamma = \kappa_\gamma = 0$ at the 95% CL, providing the first direct evidence that the photon couples to more than just the electric charge of the W boson.

B. $WW \to l\nu l\nu \quad (l = e, \mu)$

These events are selected by requiring two isolated leptons with $p_T > 15 - 25$ GeV/c, and $\not{E}_T > 20 - 25$ GeV. The main backgrounds are due to $t\bar{t}$, $Z \to \tau\tau$, and Drell-Yan production. In a 97 pb^{-1} sample DØ [13] finds 5 events, with a background of 3.1 ± 0.4 events, and sets a 95% CL upper limit on σ_{WW} of 37.1 pb. In a 108 pb^{-1} sample CDF [14] 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 $\sigma_{WW} = 9.5 \pm 1.0$ 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 $\lambda_Z = \lambda_\gamma$: $-0.62 < \Delta\kappa < 0.77$ (for $\lambda = 0$), and $-0.53 < \lambda < 0.56$ (for $\Delta\kappa = 0$).

C. $WW, WZ \to l\nu jj, lljj \quad (l = e, \mu)$

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 $\not{E}_T > 20 - 25$ GeV (or a second high p_T lepton for the $lljj$ events). The background from W+jets is large in this channel. CDF [15] uses events with $p_T(jj) > 200$ GeV/c to get anomalous coupling limits, and DØ [16] uses a binned likelihood fit to the $p_T(W)$ spectrum to get them. The limits on the anomalous couplings $\Delta\kappa$ and λ obtained by each experiment are similar, and are about a factor of 1.4 tighter than those from the $WW \to l\nu l\nu$ channel. The coupling $\lambda_Z = \kappa_Z = 0$ is excluded at $> 99\%$ CL by both ex-

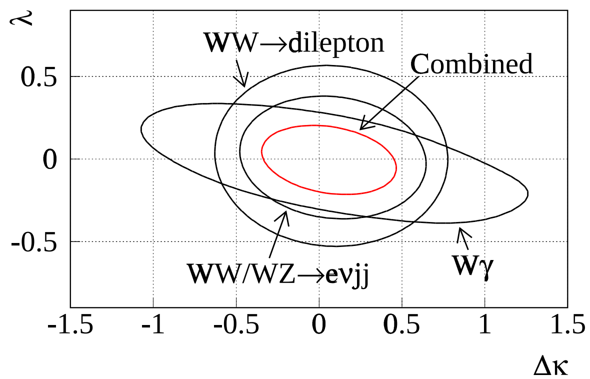

FIG. 9. *DØ contour limits on anomalous $WW\gamma$ couplings (for $\Lambda = 1.5$ TeV).*

periments, thus providing the first direct evidence for a WWZ coupling.

D. $Z\gamma$ Production

DØ [17] and CDF [12] have each measured $Z(ee)\gamma$ and $Z(\mu\mu)\gamma$ 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 spectra. The results are the outer two ellipses in Fig.8.

DØ has also measured [18] $Z(\nu\nu)\gamma$ 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, $W \to e\nu$, jet-jet and jet-γ 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 $W \to e\nu$, 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 cosmics 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.

TABLE I. *DØ limits on anomalous couplings $\alpha_{B\phi}$, $\alpha_{W\phi}$, and α_W at the 95% CL from a simultaneous fit to the $W\gamma, WW \to \ell\nu\ell\nu$, and $WW/WZ \to e\nu jj$ data. Also shown are the LEP limits, and the LEP + DØ combined limits.*

	DØ	LEP	DØ + LEP
$\alpha_{B\phi}$	-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
α_W	-0.20, 0.20	-0.21, 0.27	-0.18, 0.13

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:

$$| h_{30}^{Z,\gamma} | < 0.37 \quad \text{and} \quad | h_{40}^{Z,\gamma} | < 0.05$$

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 $WW/WZ \to e\nu jj$ 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.9, 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 α_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.

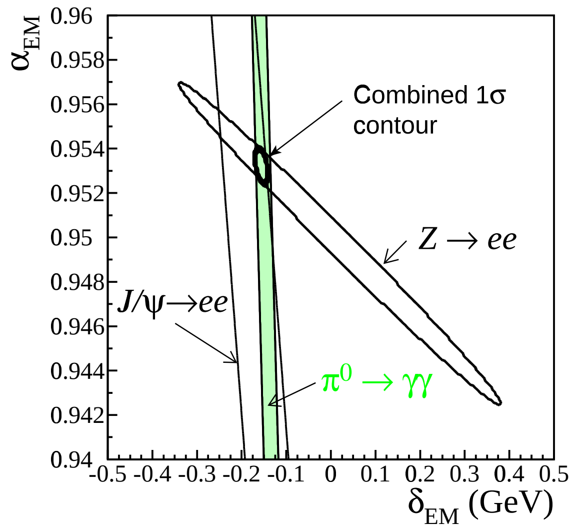

FIG. 10. *Constraints on the DØ electromagnetic energy scale parameters from collider data.*

VI. W BOSON MASS

The W boson mass is a fundamental parameter of the Standard Model. At next to leading order it can be written as:

$$M_W^2 = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F}\frac{1}{(1-(M_W^2/M_Z^2))}\frac{1}{(1-\Delta r)} \tag{3}$$

where M_Z is the Z boson mass, G_F is the Fermi coupling constant, α is the fine structure constant (evaluated at a scale=M_Z), and Δr represents the effect of radiative corrections. The parameters M_Z, G_F and α have been measured to better than 0.01%. The parameter Δr depends on the masses of particles which couple to the W boson, such as the top quark, Higgs boson or new particles. Thus a precision measurement of the W boson mass, along with a measurement of the top quark mass, can be used to constrain the Higgs boson mass or indicate the presence of new physics beyond the Standard Model.

At the Fermilab Tevatron, W bosons are produced via $p\bar{p} \to W$ + jets, and the W bosons are detected through their leptonic decays: $W \to$ lepton + ν. One can measure $P_T(\nu)$ from transverse energy balance, but one can't measure $P_L(\nu)$ because of the unknown amount of energy that went down the beampipe in the forward/backward directions. Thus a true invariant mass cannot be calculated. Instead, one calculates the "transverse mass", as given in Eq.2. The M_T distribution shows a sharp Jacobian peak at the W mass. The W mass is determined from a likelihood fit of the M_T distribution to Monte Carlo generated templates in transverse mass for different W mass values. The E_T^ν measurement depends on the "recoil" momentum of the hadrons, and thus one needs to understand the resolution of, and bias in, both 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.

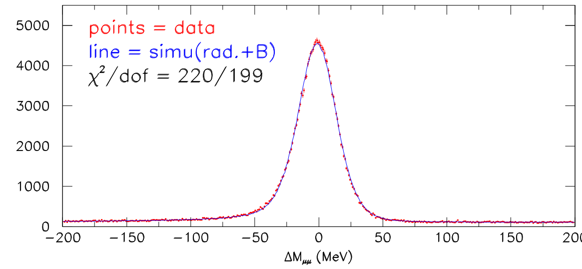

FIG. 11. *Difference between the CDF dimuon mass and the PDG value for $J/\psi \to \mu\mu$ events.*

The most recent Tevatron measurements of M_W, using the Run 1B (1994-95) data, are DØ's published result [21] using the $W \to e\nu$ channel, and CDF's preliminary result [22] using the $W \to \mu\nu$ channel. The experiments select events with an isolated, high quality lepton in the central region with $p_T > 25$ GeV/c, $\not{E}_T > 25$ GeV, and hadronic recoil $< 15-20$ GeV. This results in a sample of 28K $W \to e\nu$ events for DØ, and 21K $W \to \mu\nu$ 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 $E_{obs} = \alpha E_{true} + \delta$, and the parameters α and δ are determined from $Z \to ee, \pi^0 \to \gamma\gamma$, and $J/\psi \to ee$ collider data, as shown in Fig.10. DØ finds that $\alpha = 0.9533 \pm 0.0008$ and $\delta = -0.16^{+0.03}_{-0.21}$ GeV, including systematic errors from underlying event corrections and nonlinearity at low E_T. The uncertainty on α (δ) results in an error on M_W of 65 (20) MeV. DØ uses its $Z \to ee$ 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 $J/\psi \to \mu\mu$ 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 $Z \to \mu\mu$ 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 $p\bar{p} \to Z + X$ events to determine the hadronic recoil energy scale and resolution. DØ uses $Z \to ee$ events, and CDF uses $Z \to \mu\mu$ 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

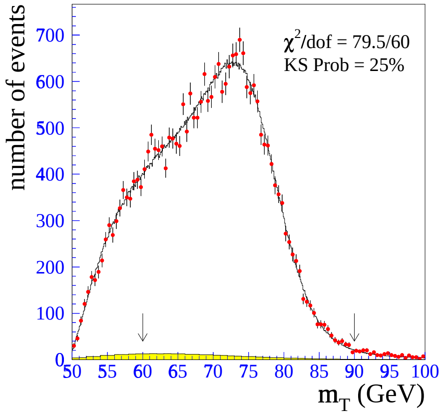

FIG. 12. *Transverse mass distribution of $W \to e\nu$ events from the DØ Run 1B data, with the best fit. The shaded distribution is the background.*

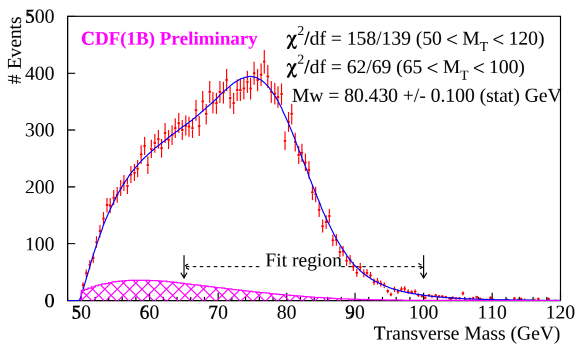

FIG. 13. *Transverse mass distribution of $W \to \mu\nu$ events from the CDF Run 1B data, with the best fit. The shaded distribution is the background.*

1B measurements are:

$$\text{DØ 1B}: M_W = 80.440 \pm 0.095 \pm 0.065 \text{ GeV/c}^2$$
$$\text{CDF 1B}: M_W = 80.430 \pm 0.100 \pm 0.120 \text{ GeV/c}^2$$

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

$$\text{DØ 1A+B}: M_W = 80.430 \pm 0.110 \text{ GeV/c}^2$$
$$\text{CDF 1A+B}: M_W = 80.375 \pm 0.120 \text{ GeV/c}^2$$

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

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

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

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

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

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

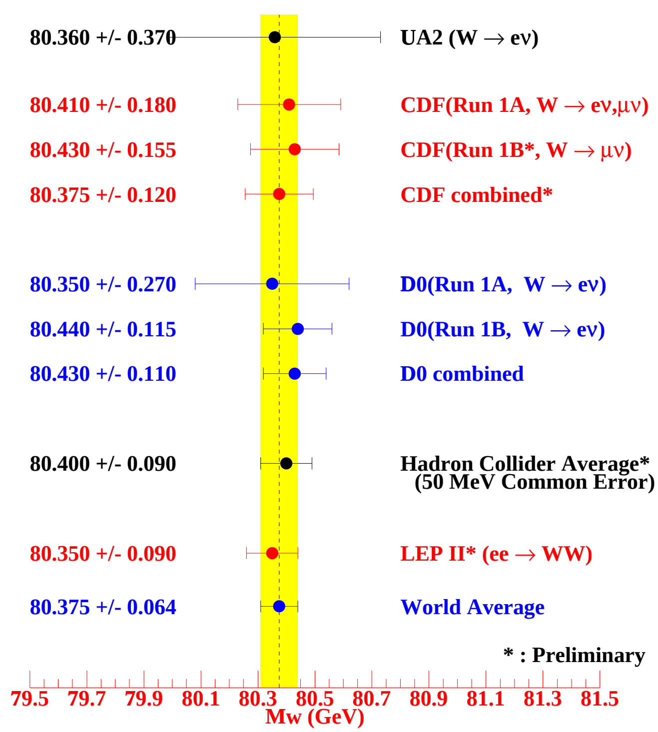

FIG. 14. *Summary of direct W mass measurements.*

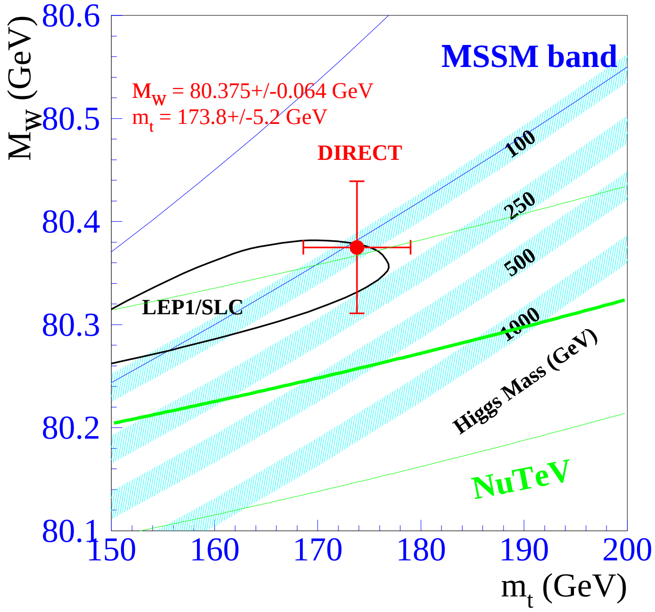

FIG. 15. *M_W vs M_{top}. The point is the combined result from direct measurements. Also shown are the allowed regions from LEP1/SLC and NuTeV, the prediction of the minimal supersymmetric model (MSSM), and the Standard Model predictions for Higgs masses from* $100-1000$ *GeV/c^2.*

is the Direct World Average, with M_{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/c^2.

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 ΔM_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 ΔM_W of about 90 MeV. Thus one expects a final Tevatron Run 1 ΔM_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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