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# MEASUREMENTS OF THE W BOSON MASS AND TRILINEAR GAUGE BOSON COUPLINGS AT THE TEVATRON

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We present measurements of the $W$ boson mass at the Tevatron based on $W \to \mu\nu$ events collected by CDF and $W \to e\nu$ events observed by DØ in Run Ib (1994–95). The $W$ boson mass measured in the preliminary CDF analysis is $80.43 \pm 0.10$ (stat) $\pm$ 0.12 (syst) GeV/$c^2$. The DØ measured value is $80.44 \pm 0.10$ (stat) $\pm 0.07$ (syst) GeV/$c^2$. We also describe measurements of the trilinear gauge boson couplings. The limits obtained on the $WW\gamma$ and $WWZ$ anomalous couplings from a combined DØ analysis using $W\gamma$, $WW \to \ell\nu\ell'\nu'$, and $WW/WZ \to e\nu jj$ production are: $-0.30 < \Delta\kappa < 0.43$, $-0.20 < \lambda < 0.20$, and $-0.52 < \Delta g_1^Z < 0.78$, for a dipole form factor scale of 2 TeV. Improved limits have been obtained by combining these results with the limits derived from the LEP experiments.

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## 1 Measurement of the W Boson Mass

The mass of the $W$ boson is a fundamental parameter of the standard model and is related to the Fermi constant $G_F$, the electromagnetic coupling constant $\alpha_{EM}$, the $Z$ boson mass $m_Z$, and $\Delta r$, which represents the effects of radiative corrections. $G_F$, $\alpha_{EM}$, and $m_Z$ are all measured [1] with high precision. In the standard model $\Delta r$ depends on the top quark and Higgs boson masses and in theories beyond the standard model it depends on the particle spectrum of the new theory. Therefore, together with a measurement of the top mass, a precise measurement of the $W$ boson mass can be used to constrain the Higgs mass in the standard model and to constrain theories beyond the standard model.

The recent measurement published by DØ [2] and the preliminary measurement from CDF [3], both from Run Ib data (1994–95), are briefly described here. The measurements are made using a fit to the observed transverse mass spectrum $m_T = \sqrt{2p_T^\ell \not{E}_T(1-\cos\Delta\phi)}$ in $W \to \ell\nu$ events. The transverse mass spectrum is modeled using a Monte Carlo event generator which incorporates a $W$ boson production model and a detailed model of the detector response, which is calibrated using collider data.

Calibration of the muon momentum scale is achieved in CDF by comparing the reconstructed $J/\psi \to \mu^+\mu^-$ mass (Fig. 1) to the world average. The error in the $W$ boson mass due to the momentum scale uncertainty is $\delta m_W = 40$ MeV/$c^2$, while the momentum resolution contributes $\delta m_W = 25$ MeV/$c^2$.

In DØ the electromagnetic calorimeter energy scale is determined from test beam measurements and collider data. The observed energy $E_{\rm obs}$ is parametrized as $E_{\rm obs} = \delta + \alpha E_{\rm true}$, and the constants $\delta$ and $\alpha$ are determined from $\pi^0 \to \gamma\gamma$, $J/\psi \to ee$, and $Z \to ee$ events as shown in Fig. 2. The resulting values are $\alpha = 0.9533 \pm 0.0008$, and $\delta = (0.16^{+0.03}_{-0.21})$ GeV, where the errors include the systematic uncertainty due to underlying event corrections and non-linearity of the response at low $E_T$. The contribution of the energy scale uncertainty to the $W$ boson mass error is $\delta m_W = 70$ MeV/$c^2$. The energy resolution contributes $\delta m_W = 25$ MeV/$c^2$.

In both CDF and DØ the response of the detector to the recoil system, (hadrons recoiling against the $W$ boson, interactions of the proton and antiproton spectator quarks, and energy from multiple interactions), is calibrated using the transverse energy balance in $Z \to ee$ decays. The method employed by DØ is illustrated in Fig. 3. The recoil response $R$ is defined by

$$|\mathbf{u}_T \cdot \hat{\mathbf{q}}_T| = R|\mathbf{q}_T|$$

where $\mathbf{u}_T$ is the transverse momentum of the recoil system, $\mathbf{q}_T = q_T\hat{\mathbf{q}}_T$ is the transverse momentum of the $Z$ boson. The LHS of this equation is the projection of the recoil system transverse momentum along the $Z$ boson transverse momentum vector, and for an ideal detector $R = 1$. A detailed GEANT-based Monte Carlo simulation shows that the response can be parametrized using two constants $\alpha$ and $\beta$ (see Fig. 3), which are determined using $Z \to ee$ data, yielding $\alpha = 0.693 \pm 0.060$, and $\beta = 0.040 \pm 0.021$. The resulting contribution to the $W$ boson mass error is $\delta m_W = 20$ MeV/$c^2$. The contribution from the recoil resolution is $\delta m_W = 25$ MeV/$c^2$.

Fits to the transverse momentum distributions are shown in Fig. 4 and Fig. 5. The CDF data yield the result $m_W = 80.43 \pm 0.10$ (stat) $\pm$ 0.12 (syst) GeV/$c^2$, and the DØ result is $m_W = 80.44 \pm 0.10$ (stat) $\pm$ 0.07 (syst) GeV/$c^2$. Table 1 itemizes the sources of uncertainty in the measurements.

Combining with previous measurements[4] from UA2, CDF and DØ yields a hadron collider average of $m_W = 80.40 \pm 0.09$ GeV/$c^2$. The LEP average $W$ boson mass reported at this conference[5] is $m_W = 80.35 \pm 0.09$ GeV/$c^2$. Combining these results yields a new world average of $m_W = 80.375 \pm 0.065$ GeV/$c^2$. Combining this result with the Tevatron top mass measurement[6] ($m_t = 174.1 \pm 5.4$ GeV/$c^2$) allows a comparison with the predictions of the standard model[7] and the minimal supersymmetric model[8], as shown in Fig. 6.

| | DØ Run Ib [GeV/$c^2$] | CDF Run Ib prelim. [GeV/$c^2$] |
|---|---|---|
| $W$ Statistics | 70 | 100 |
| | | |
| $E(e)$ or $p(\mu)$ scale | 70 | 40 |
| $e$ or $\mu$ resoultion | 40 | 25 |
| Recoil modeling | 30 | 90 |
| Selection bias | – | 20 |
| | | |
| Backgrounds | 10 | 25 |
| | | |
| $W$ width | 10 | 10 |
| $W$ production (incl. pdf's) | 25 | 50 |
| QCD / QED corrections | 15 | 30 |

Table 1: Contributions to the total $W$ boson mass uncertainty in the DØ and CDF Run Ib analyses.

## 2 Trilinear Gauge Boson Couplings

Gauge invariance under the group SU(2) $\times$ U(1), an underlying principle at the heart of the standard model, leads to the prediction of gauge boson self-couplings (e.g. the $WW\gamma$ and $WWZ$ vertex couplings). These couplings may be studied at the Tevatron through the production of gauge boson pairs ($W\gamma$, $WW$, $WZ$). Deviations from the standard model would provide important information about the kind of new physics beyond the standard model.

To test the agreement with the standard model and to set limits on anomalous couplings the $WWV$ ($V = \gamma, Z$) vertices are parametrized using the effective Lagrangian of Ref. 9. Assuming electromagnetic gauge invariance, and invariance under Lorentz and CP transformations the effective Lagrangian is reduced to a function of five dimensionless coupling parameters $g_1^Z, \kappa_V$, and $\lambda_V$. In the SM at tree level $g_1^Z = 1, \Delta\kappa_V \equiv \kappa_V - 1 = 0$ and $\lambda_V = 0$.

The effective Lagrangian formalism is valid only at energies much smaller than the scale of new physics. At very high energies the formalism breaks down and the full particle spectrum of the new theory must be included to ensure unitarization. In the hadron collider experiments it is customary to ensure tree level unitarity at high energies using model-dependent dipole form factors for all the couplings, e.g.

$$\Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{(1 + \hat{s}/\Lambda_{\mathrm{FF}}^2)^2}$$

where $\Delta\kappa$ = value of coupling parameter at $\hat{s} = 0$, $\hat{s}$ = square of the invariant mass of the partonic subprocess, and $\Lambda_{\mathrm{FF}}$ = form factor scale, typically taken to be about 2 TeV.

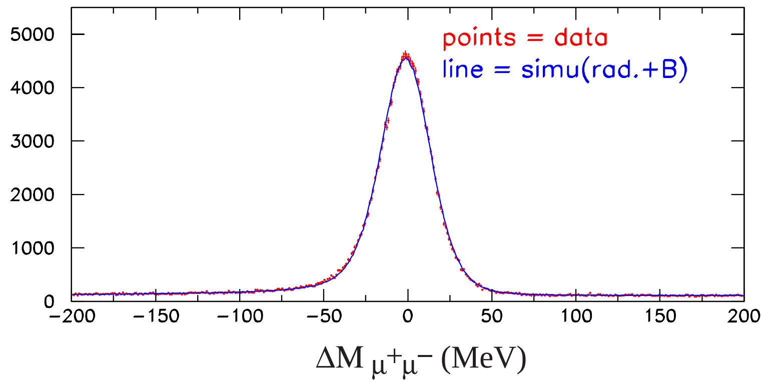


Figure 1: Dimuom mass peak obtained from reconstructed $J/\psi \to \mu^+\mu^-$ events in CDF. The points are the data and the line is the simulation, which includes QED corrections and effects of $B$-decays on the beam-constrained momentum measurement.

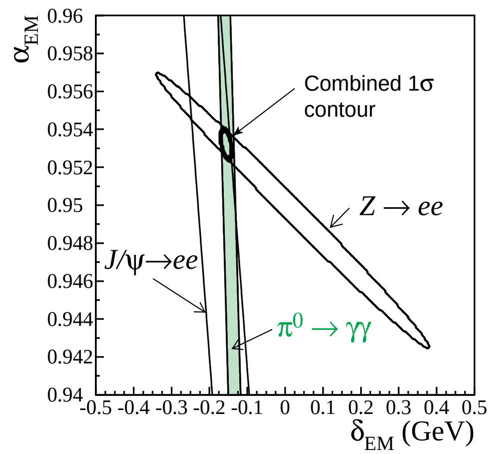


Figure 2: Constraints on the parameters $\alpha$ and $\delta$ obtained in the DØ analysis using $\pi^0 \to \gamma\gamma$, $J/\psi \to ee$, and $Z \to ee$ events.

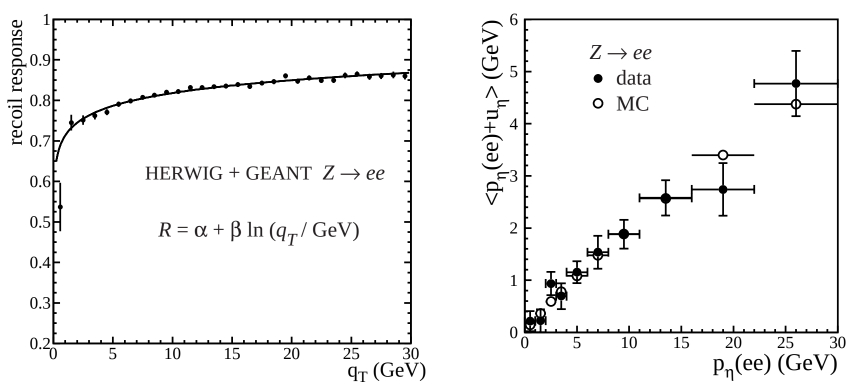


Figure 3: Determination of the hadronic recoil response in DØ. (a) simulated recoil response $R$ versus $Z$ boson transverse momentum $q_T$. The points are from a detailed GEANT simulation of the DØ detector and the line is the result of a fit using the function shown. (b) $e^+e^-$-pair plus recoil system momentum $< p_\eta(ee) + u_\eta >$ versus the momentum of the $e^+e^-$-pair $p_\eta(ee)$. The quantities are projected along the $\eta$-axis, defined as the inner bisector of the $e^+$ and $e^-$ in the transverse plane.

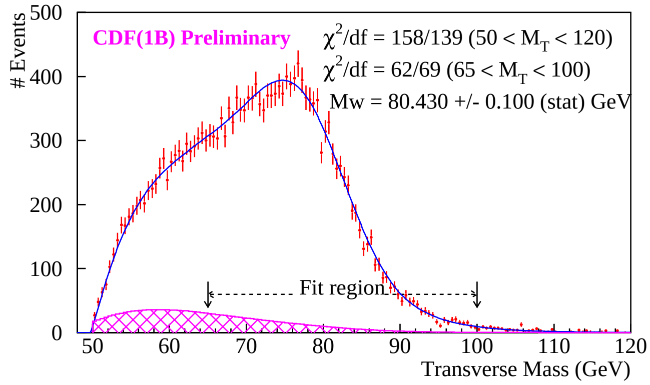


Figure 4: Transverse mass distribution observed by CDF (points) and modeled by the Monte Carlo simulation for the best fit value of the $W$ boson mass (curve). The contribution from the background is also shown (shaded distribution).

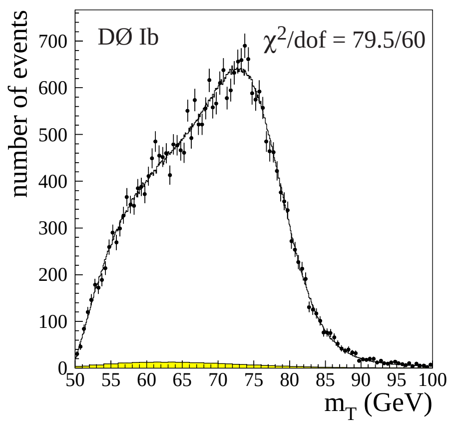


Figure 5: Transverse mass distribution observed by DØ (points) and modeled by the Monte Carlo simulation for the best fit value of the $W$ boson mass (curve). The contribution from the background is also shown (shaded distribution).

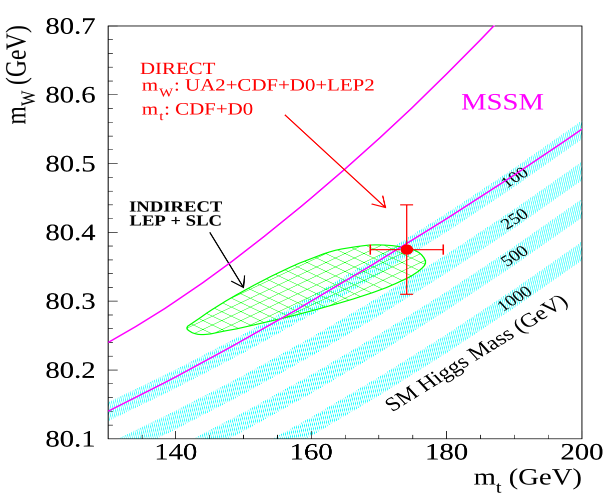


Figure 6: $W$ boson mass $m_W$ plotted versus top mass $m_t$. The data point represents the combined result from direct measurements. The shaded area is the allowed region from fits to the electroweak prarameters. Also shown are the standard model predictions for higgs masses between 100$-$1000 GeV/$c^2$ and the prediction of the minimal supersymmetric model (MSSM).

Limits have been obtained by CDF and DØ using $W\gamma$ production [10], and the processes $WW \to \ell\nu\ell'\nu'$ [11], and $WW/WZ \to \ell\nu jj/\ell^+\ell^- jj$ [12]. A review of these results is given in Ref. 13. In the following subsection we report on recent limits derived by DØ using a combination of these data [14].

### 2.1 *DØ Combined Analysis of $WW\gamma$ and $WWZ$ Couplings*

DØ has recently performed a simultaneous fit to the photon $p_T$ distribution in the $W\gamma$ data, the lepton $p_T$ distribution in the $WW \to \ell\nu\ell'\nu'$ data, and the $p_T^{e\nu}$ distribution in the $WW/WZ \to e\nu jj$ data. Limits on the $WW\gamma$ and $WWZ$ coupling parameters are extracted from the fit, taking care to account for correlations between the uncertainties on the integrated luminosity, the selection efficiencies, and the background estimates. The results are given in Table 2.

The DØ fit has also been performed using the alternative parametrization of the couplings used by the LEP groups, in terms of the parameters $\alpha_{B\phi}, \alpha_{W\phi}$, and $\alpha_W$[a]. The results are shown in Table 3. Also, shown are the limits obtained by combining with the LEP limits reported at this conference [15]. Note that the LEP limits should be multiplied by a factor $(1 + s/\Lambda_{\rm FF}^2)^2$ to compare directly with the DØ results. At the LEP energy, $\sqrt{s}$ = 183 GeV, this factor is only 1.017 for $\Lambda_{\rm FF}$ = 2 TeV. Since this is a negligible correction, it was not taken into account.

The LEP limits are based on approximately 55 $\mathrm{pb}^{-1}$ of data per experiment at $\sqrt{s} =$ 183 GeV. They are complimentary to the Tevatron limits because they are obtained from a different process (i.e. $e^+e^- \to W^+W^-$) using angular distributions of the decay products.

| Coupling | $\Lambda_{\rm FF} = 1.5$ TeV | $\Lambda_{\rm FF} = 2.0$ TeV |
|---|---|---|
| $\Delta\kappa_\gamma$ | $-0.63$, 0.75 | $-0.59$, 0.72 |
| $\lambda_\gamma$ | $-0.27$, 0.25 | $-0.26$, 0.24 |
| $\Delta\kappa_Z$ | $-0.46$, 0.64 | $-0.42$, 0.59 |
| $\lambda_Z$ | $-0.33$, 0.37 | $-0.31$, 0.34 |
| $\Delta g_1^Z$ | $-0.56$, 0.86 | $-0.52$, 0.78 |
| Assuming $\kappa_\gamma = \kappa_Z = \kappa$, $\lambda_\gamma = \lambda_Z = \lambda$: | | |
| $\Delta\kappa$ | $-0.33$, 0.46 | $-0.30$, 0.43 |
| $\lambda$ | $-0.21$, 0.21 | $-0.20$, 0.20 |

Table 2: DØ limits on anomalous couplings 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.

## 3 Summary

The $W$ boson mass has been measured by CDF and DØ using Run Ib data. The DØ result is $m_W = 80.44 \pm 0.10$ (stat) $\pm\, 0.07$ (syst) GeV/$c^2$, and the preliminary CDF result is $m_W = 80.43 \pm 0.10$ (stat) $\pm\, 0.12$ (syst) GeV/$c^2$.

[a] These are related to the previous set by

$$\Delta g_1^Z = \alpha_{W\phi}/\cos^2\theta_W \qquad \lambda_\gamma = \lambda_Z = \alpha_W$$
$$\Delta\kappa_\gamma = \alpha_{W\phi} + \alpha_{B\phi} \qquad \Delta\kappa_Z = \alpha_{W\phi} - \tan^2\theta_W \alpha_{B\phi},$$

where $\theta_W$ is the weak mixing angle.

| Coupling | DØ | LEP combined | DØ + LEP combined |
|---|---|---|---|
| $\alpha_{B\phi}$ | −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 |

Table 3: DØ limits on anomalous couplings $\alpha_{B\phi}$, $\alpha_{W\phi}$, $\alpha_W$, and $\Delta g_1^Z$ at the 95% CL from a simultaneous fit to the $W\gamma$, $WW \rightarrow \ell\nu\ell'\nu'$, and $WW/WZ \rightarrow e\nu jj$ data. Also shown are the LEP limits from a combination of ALEPH, DELPH, L3 and OPAL data, and the LEP + DØ combined limits.

Measurements of the trilinear gague boson couplings were reported by DØ using a combined fit to $W\gamma$ data, $WW \rightarrow \ell\nu\ell'\nu'$ data, and $WW/WZ \rightarrow e\nu jj$ data. The DØ limits are comparable in sensitivity and complimentary in nature to the combined results from the four LEP experiments, and DØ and LEP have now produced combined limits.

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