Fermi National Accelerator Laboratory

FERMILAB-Conf-94/153-E

CDF

The Measurement of the *W* Boson Mass from CDF

The CDF Collaboration

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P.O. Box 500, Batavia, Illinois 60510

June 1994

Submitted to the *27th International Conference on High Energy Physics*, Glasgow, Scotland, July 20-27, 1994

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

CDF/PUB/ELECTROWEAK/PUBLIC/2632
FERMILAB-CONF-94/153-E

ICHEP94
gls0414

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Abstract

We have made a preliminary determination of the W boson mass M_W = 80.38 ± 0.23 GeV/c^2 from a combined analysis of $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV. The electron data alone yields M_W = 80.47 ± 0.15(stat.) ± 0.25(syst.) GeV/c^2, while the muon data gives M_W = 80.29 ± 0.20(stat.) ± 0.24(syst.) GeV/c^2.

1 Introduction

Recent results from LEP experiments have substantially improved our knowledge of the Z boson. However, hadron colliders remain our only source of direct measurements of the W boson. There have been measurements of the W boson mass from the UA2 [4] and CDF [3] collaborations. The W mass continues to be a subject of great interest in testing the Standard Model. We present a preliminary measurement of the W boson mass using our recent Run 1a data sample, which corresponds to a total integrated luminosity of 19.7 pb^{-1}, taken between August 1992 and May 1993 at the Fermilab Tevatron. The present analysis has benefitted from the factor five increase in W statistics, and in addition the larger sample of $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events allows us to reduce the systematic errors in the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ event reconstruction.

The W mass is measured from fits to transverse mass spectra M_T^W in both $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays, where M_T^W is constructed from the transverse momenta, $\vec{P}_T^{lepton}$ and $\vec{P}_T^{\nu}$, of the electron (or muon) and neutrino:

$$M_T^W = \sqrt{2P_T^{lepton}P_T^{\nu}(1 - cos\phi_{lepton,\nu})}$$

with $\phi_{lepton,\nu}$ being the azimuthal angle between the lepton and the neutrino direction. This paper describes the lepton momentum measurement in section 2, the neutrino

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Submitted 27th International Conference on High Energy Physics, University of Glasgow, Glasgow, Scotland, July 20-27, 1994.

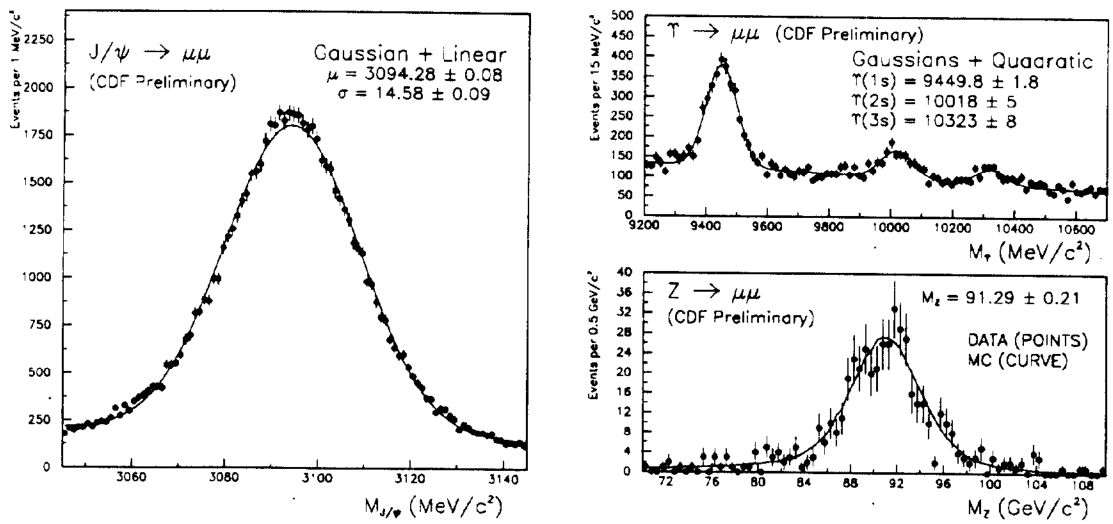


Figure 1: The mass spectra for the $\mu^+\mu^-$ final state in the region of the J/ψ mass (left) and in the region of the Υ and Z masses (right).

momentum measurement in section 3, the event selection in section 4, the physics and detector model in section 5, and the fitting procedure in section 6. The systematic uncertainties are discussed in section 7 and we present the results in section 8.

2 Lepton Momentum Measurement

The muon momentum is measured from the central tracking chamber (CTC) [1] as it traverses a 14 kG magnetic field, while the electron energy is measured from the central electromagnetic calorimeter (CEM) [2]. The CTC momentum scale is determined by rescaling the invariant mass of the fitted $J/\psi \to \mu^+\mu^-$ signal to the value given by the Particle Data Group (PDG). We have measured the J/ψ mass to be 3094.28 $\pm$ 0.07(stat.) MeV as shown in Fig. 1. After applying corrections due to radiation, energy loss in the detector material, and alignment effects, the mass of the J/ψ is 3094.58 $\pm$ 2.2 MeV. The total systematic uncertainty of 2.2 MeV on the J/ψ mass translates to a 60 MeV uncertainty on the W mass. The corrections and the systematic uncertainties are summarized in the following table. Normalizing the measured J/ψ mass to the PDG value, a scale factor of 1.00076 $\pm$ 0.00071 is extracted. This factor is applied to all the CTC tracks.

	$\Delta M_{J/\psi}$	Uncertainty
Energy Losses in tracking volume	+1.0 MeV	1.0 MeV
Geometry effects (alignment)	−1.0 MeV	1.0 MeV
Beam Constraint for non-prompt tracks		0.5 MeV
Residual B-field non-uniformity		1.1 MeV
Time Variations		1.0 MeV
Non-linearities		0.5 MeV
Background		0.1 MeV
Radiative Effects	+0.3 MeV	0.3 MeV
Total	+0.3 MeV	2.2 MeV

As a consistency check for the CTC scale, especially for high P_T tracks, the masses of the Υ(1s), Υ(2s), Υ(3s) states and the mass of the Z (see Figs. 1) are measured. The masses before and after the scale correction are listed in the following table. The masses after the scale correction agree with the PDF values very well. For the Z mass, the fitted peak includes the contributions from the Drell-Yan continuum and from radiative decays of the Z boson.

Sample	CDF	PDG	SCALED	Unit
Υ (1s)	9449.8 ±1.8	9460.3 ±0.2	9457.0±1.8±7	MeV
Υ (2s)	10018 ±5	10023.3±0.3	10026 ±5 ±7	MeV
Υ (3s)	10323 ±8	10355.5 ±0.5	10331 ±8 ±7	MeV
Z	91.22±0.21	91.173±0.020	91.29±0.21±0.065	GeV

The CEM scale is determined by fitting the E/P lineshape of electrons from W decays to a simulated lineshape which includes the effects of radiative W decays and external bremsstrahlung in the detector material. Before the scale is determined, the CEM response as a function of the electron impact point is corrected to be as uniform as possible by using a large sample of low transverse momentum electrons, resulting in better resolution for the electron energy. The E/P distribution for the W electrons after this correction is shown in Fig. 2, where E and P are the CEM and CTC measurements of the electron energy and momentum respectively. The long tail on the right-hand side of the distribution is due to internal and external bremsstrahlung emitted by the electron before entering the tracking volume. Since the photon is nearly collinear with the electron, the CEM E measurement is largely unaffected by the bremsstrahlung but the CTC P measurement is lowered, resulting in the long tail. The solid histogram is from a radiative Monte Carlo which includes the contributions from both internal and external radiation of photons. The CEM scale determined with this method provides a statistical precision of 0.08% and a systematic uncertainty of 0.13%.

As a cross check for the CEM scale, the invariant mass of $Z \rightarrow e^+e^-$ events with both electrons in the central calorimeter is reconstructed. A simulation including

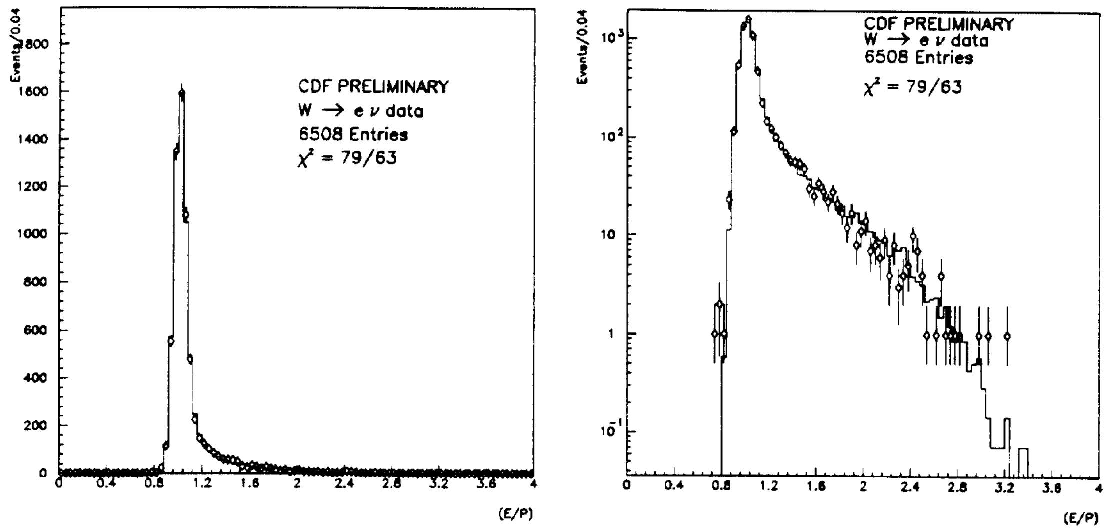


Figure 2: Ratio of the CEM measurement of electron energy (E) to the CTC measurement of electron momentum (P) for the $W \rightarrow e\nu$ sample on both linear (left) and logarithmic (right) scales. The points are the data and the histogram is the radiative simulation.

contributions from the Drell-Yan continuum and radiative Z decays is used to fit the invariant mass distribution. The best fit is 90.87 $\pm$ 0.20(stat.) $\pm$ 0.16(syst.) GeV.

3 Neutrino Momentum Measurement

The neutrino momentum is determined by measuring the energy of all of the hadrons in the event which recoil against the W. We remove the calorimeter towers associated with the electron or muon, and replace them with the average hadronic energy, 30 MeV per tower, from the underlying event in our W sample. Then, the momentum of the recoiling hadrons is the vector sum of E_T

$$\vec{P}_T^{hadron} = (\Sigma E_{tower} \vec{v}_{tower})_T$$

with E_{tower} being the energy in a given calorimeter tower in the pseudorapidity region $|\eta| < 3.6$ and $\vec{v}_{tower}$ being a unit vector from the event vertex to the center of the given tower. The missing momentum, thus the neutrino momentum, is reconstructed from the transverse energy balance

$$\vec{P}_T^{\nu} = -\vec{P}_T^{lepton} - \vec{P}_T^{hadron}.$$

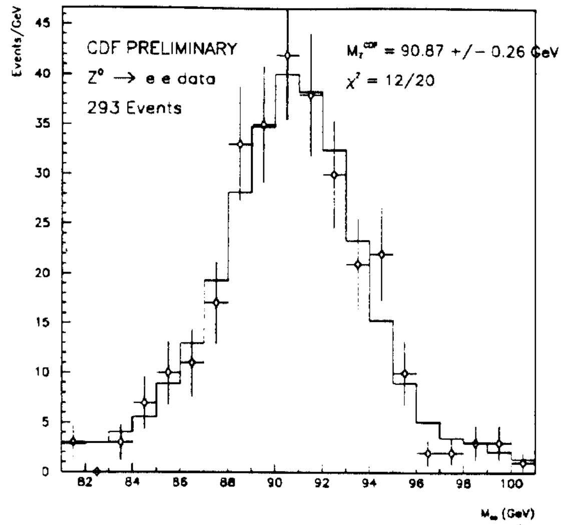


Figure 3: The mass spectrum of the $Z \to e^+e^-$ sample. The histogram shows the best fit to the data.

4 Event Selection

Events are removed if any detector elements used in this analysis were not functioning properly or the running conditions were not stable. This removes $\sim$ 10 % of the events. Events are also required to satisfy the following criteria:

- high lepton transverse momentum, P_T^e or $P_T^\mu > 25$ GeV,
- high neutrino transverse momentum, $P_T^\nu > 25$ GeV,
- high transverse mass, $60 < M_T^W < 100$ GeV,
- no jets with $E_T^{jet} > 20$ GeV,
- no other tracks with $P_T > 20$ GeV,
- the lepton track must be isolated, and
- the lepton satisfies tight fiducial requirements.

The total number of $W \to e\nu$ events is 6421 and the number of $W \to \mu\nu$ events is 4090.

5 Physics and Detector Model

W events are generated with a leading-order calculation using the MRS D$'_-$ parton distribution function. The bosons are given transverse momentum with a subsequent boost. To model the transverse mass spectrum, one must calibrate the detector response to the hadrons recoiling against the W. However, the detector response to the low-energy hadrons is poorly known. Since the production properties of Z bosons are very similar to the production properties of W bosons, and both leptons from

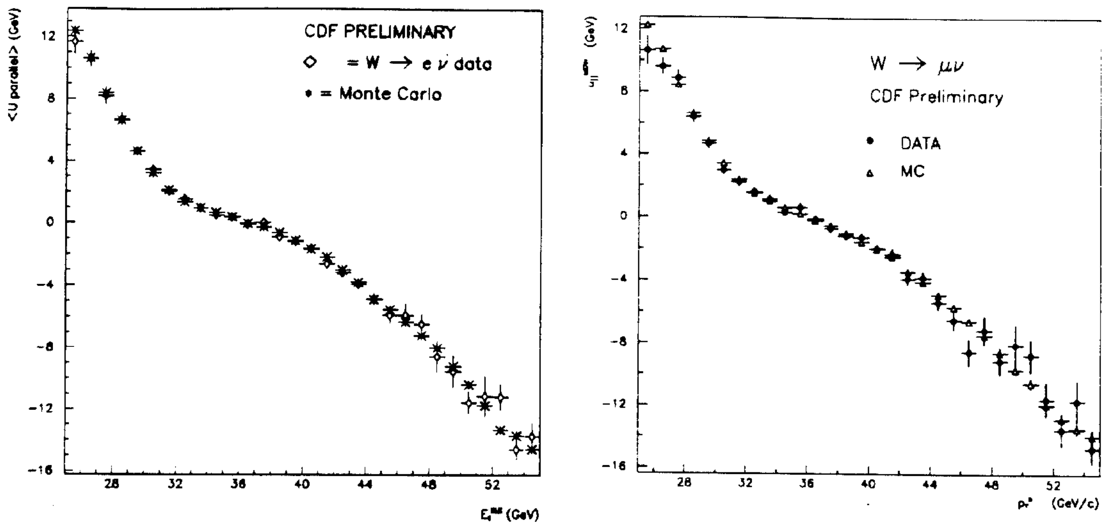


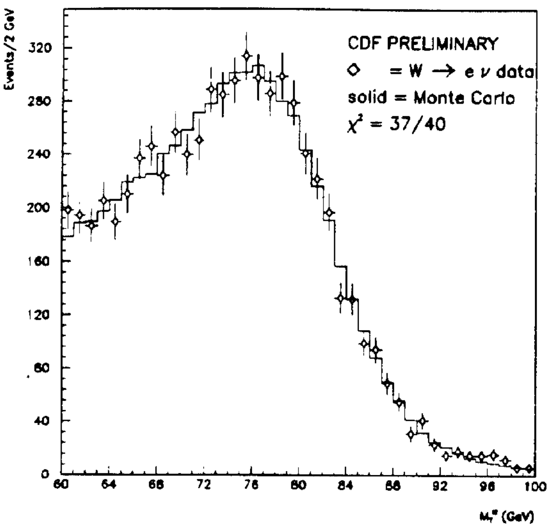
Figure 4: The $< u_{||} >$ as a function of the lepton P_T. The left(right) figure is from the $W \rightarrow e\nu (W \rightarrow \mu\nu)$ decays for the data and the simulation.

Z decays are measured with better resolution than the recoiling hadrons, we make use of the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events to model the detector response to the recoiling hadrons. When a W is generated with a given P_T, the $\vec{P}_T^{hadron}$ against the W is simulated by using the $\vec{P}_T^{hadron}$ against a Z event with the same P_T from the data. The advantage of this method is that there are no detector resolutions which need to be tuned to the data. Only the input P_T^W distribution for the generated W events needs to be tuned.

The vector $\vec{P}_T^{hadron}$ can be decomposed into two quantities, $u_{||}$ and $u_{\perp}$, which are the components parallel and perpendicular to the electron direction. The value of $u_{||}$ contains most of the transverse mass information and it is the quantity sensitive to the electron selection cuts, the residual leakage of the lepton energy, and the energy deposited under the lepton by the underlying event. Fig. 4 shows that the bias on $u_{||}$ in the data is well modelled by the simulation over the full range of P_T^{lepton}. Similar agreement is seen over the full range of P_T^{ν} and M_T^W. The measured offsets in $u_{||}$ in the our data sample and in the simulation are -405 ± 65 MeV and -330 MeV for the $W \rightarrow e\nu$ decays and -496 ± 83 MeV and -442 MeV for the $W \rightarrow \mu\nu$ decays. The differences between the data and the simulation are not statistically significant and thus the statistical errors are taken as systematic uncertainties.

6 Fitting Procedure

Transverse mass spectra are generated in the region of $60 < M_T^W < 100$ GeV with various W masses and W widths. The data are compared to the simulation at each



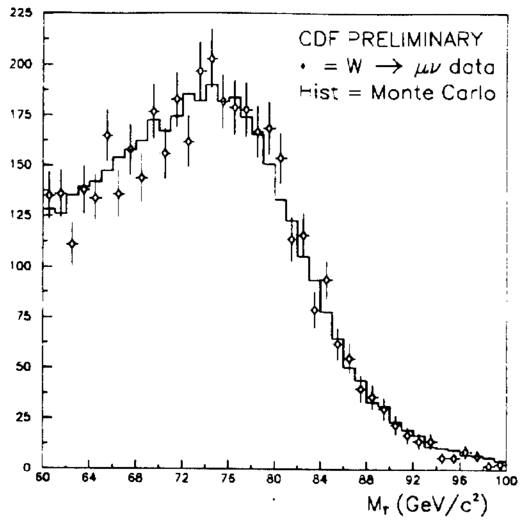


Figure 5: The transverse mass spectra of the data (points) and the best-fit (histograms) for the $W \rightarrow e\nu$ (left) and $W \rightarrow \mu\nu$ (right) samples.

W mass and W width and a log-likelihood is calculated. The log-likelihood points are fit to a parabola whose maximum value occurs at the most probable mass and width combination. The transverse mass spectra for the data used to fit the W mass and the best-fit lineshapes are shown in Fig. 5.

7 Systematic Uncertainties and Corrections

The individual uncertainties and corrections in the W mass measurement are briefly described, followed by a summary of the systematic uncertainties .

Lepton Momentum Scale: The uncertainty on the muon momentum scale comes from the CTC scale and it is 60 MeV as explained in section 2. For the electrons, in addition to the CTC scale uncertainty, there is a 120 MeV uncertainty on the CEM scale from the E/P lineshape fitting procedure. The total uncertainty for electrons is then 130 MeV.

Lepton Momentum Resolution: The electron and muon momentum resolutions were extracted from the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ widths respectively. The electron momentum resolution is

$$(\delta E/E)^2 = (13.5\%/\sqrt{E_T})^2 + (2.1 \pm 1.0\%)^2$$

and the muon momentum resolution is

$$\delta P_T/P_T = (0.09 \pm 0.02)\% \cdot P_T.$$

These uncertainties lead to uncertainties of 140 MeV and 120 MeV in the W mass, respectively.

Neutrino Scale and Lepton Efficiency: Efficiency of leptons close to the direction of the recoiling hadrons decreases, which will result in a bias on $u_{||}$. Any residual leakage from the lepton energy into surrounding calorimeter towers or errors in accounting for the energy deposited under the lepton by the underlying event will also induce a bias on $u_{||}$. These are checked by comparing $< u_{||} >$ between the data and the modeling. The difference is not statistically significant and the statistical uncertainties on $< u_{||} >$ are taken as systematic uncertainties, thus they are 70 and 90 MeV for the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays respectively.

P_T^W Distributions: The systematic effects due to the P_T^W distributions were investigated by scaling the input P_T^W distribution up and down. This gives 40 and 70 MeV for the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays. The modelling of the detector response to P_T^W is derived from the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events and thus effects from Z statistics and lepton resolution need to be taken into account. The uncertainties are 20 MeV from the Z statistics and 80 MeV from the lepton resolutions. All of these might be correlated but in this preliminary analysis, we take all of them in quadrature. The total uncertainties are 90 and 110 MeV for the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays.

Structure Functions: We have studied the variations in the fitted W mass for most of the available structure functions such as the GRV set, the MT sets, the old MRS sets, the recent MRS sets, and the CTEQ 1 and CTEQ 2 sets. The extreme variations $\pm$ 100 MeV are taken as a conservative uncertainty.

Radiative Correction: In order to study the W mass shift due to radiative W decays, the decays $W \rightarrow e\nu\gamma$ and $W \rightarrow \mu\nu\gamma$ are simulated with an $O(\alpha)$ Monte Carlo program [5]. The photon is lost when it lands in the calorimeter towers traversed by the muon, while it is included in the electron energy when it lands in the towers traversed by the electron. Otherwise, the photon energy is added to $P_T^{hadrons}$. The corrections due to the radiation in the W mass are +80 MeV and +154 MeV for the $W \rightarrow e\nu\gamma$ and $W \rightarrow \mu\nu\gamma$ decays respectively.

Backgrounds: The largest background (4.35$\pm$0.64 %) comes from the presence of $Z \rightarrow \mu^+\mu^-$ events in the $W \rightarrow \mu\nu$ sample. This background is large because neither the CTC nor the muon chambers cover the high η region. Another significant background ($\sim$ 1.2 %) comes from the $W \rightarrow \tau\nu$ where $\tau \rightarrow e\nu\nu$ in the $W \rightarrow e\nu$ sample or $\tau \rightarrow \mu\nu\nu$ in the $W \rightarrow \mu\nu$ sample. There is also a relatively large cosmic ray background ($\sim$0.8%) in the $W \rightarrow \mu\nu$ sample. QCD and $Z \rightarrow \tau^+\tau^-$ backgrounds are small. The M_T distributions of the backgrounds are shown in Fig. 6. The corrections due to the backgrounds in the W mass are +80 $\pm$ 50 MeV for the $W \rightarrow e\nu$ sample and +232 $\pm$ 50 MeV for the $W \rightarrow \mu\nu$ sample.

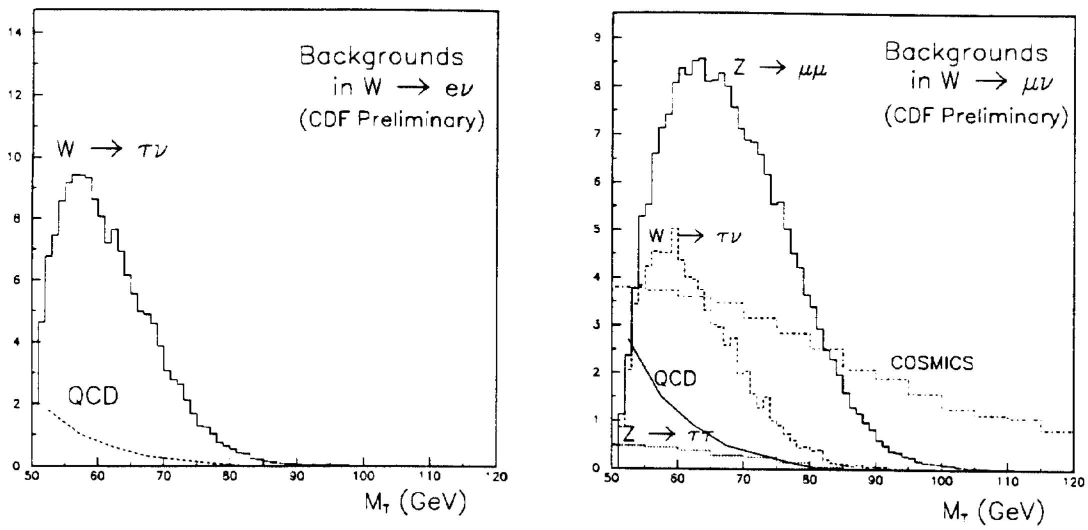


Figure 6: The M_T^W distributions of the backgrounds in the $W \to e\nu$ sample (left) and the $W \to \mu\nu$ sample (right).

8 Results

We obtain the preliminary W mass of

$$M_W = 80.47 \pm 0.15(\text{stat.}) \pm 0.25(\text{syst.})\ \text{GeV/c}^2, \text{ using the } W \to e\nu \text{ decays [7]},$$

and

$$M_W = 80.29 \pm 0.20(\text{stat.}) \pm 0.24(\text{syst.})\ \text{GeV/c}^2, \text{ using the } W \to \mu\nu \text{ decays}$$

where the W width has been fixed at 2.1 GeV. Fits in which the W width is allowed to vary, as well as fits to the P_T^{lepton} distributions and to the P_T^{ν} distributions give consistent results. The combined results from the $W \to e\nu$ and $W \to \mu\nu$ decays give

$$M_W = 80.38 \pm 0.23\ \text{GeV/c}^2\ [8].$$

In Fig. 7, we compare this measurement to other measurements by the CDF [3], UA2 [4] and D0 [6] experiments. Combining these W mass measurements, assuming a common error of 100 MeV/c^2 for the structure function uncertainty, gives

$$M_W = 80.23 \pm 0.18\ \text{GeV/c}^2,$$

which is in a good agreement with the LEP prediction [9] for the W mass. This agreement is a stringent test of the Standard Model. The combined W mass measurement is also compared with the Standard Model prediction for the relation between the W mass and the top quark mass for various values of the Higgs mass as shown in Fig. 8.

Table 1: Uncertainties (MeV) in the W mass measurement from the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays. The last three columns list correlated uncertainties between the two samples and uncorrelated uncertainties.

	$W\rightarrow e\nu$	$W\rightarrow \mu\nu$	Correlated	Uncorrelated $W\rightarrow e\nu$	Uncorrelated $W\rightarrow \mu\nu$
Statistical	150	200		150	200
Momentum Scale	130	60	60	120	
Systematics	210	220			
Momentum Resolution	140	120		140	120
P_T^W	90	110	80	40	70
$u_{\parallel}$	70	90		70	90
Backgrounds	50	50		50	50
Fitting	20	20		20	20
Structure Functions	100	100	100		
Total	290	300	140	260	270

The present analysis is still preliminary. We anticipate further reductions in the systematic uncertainties before the analysis is complete. One source of this reduction is an improvement in our knowledge of the lepton momentum resolution. Another comes from the use of our W asymmetry measurement [11] which reduces the strucure function uncertainty. We have been collecting additional data since November 1993, and expect to acquire an additional factor of four over the present analysis, leading to further imporvements in our results.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the A. P. Sloan Foundation; and the Alexander von Humboldt-Stiftung.

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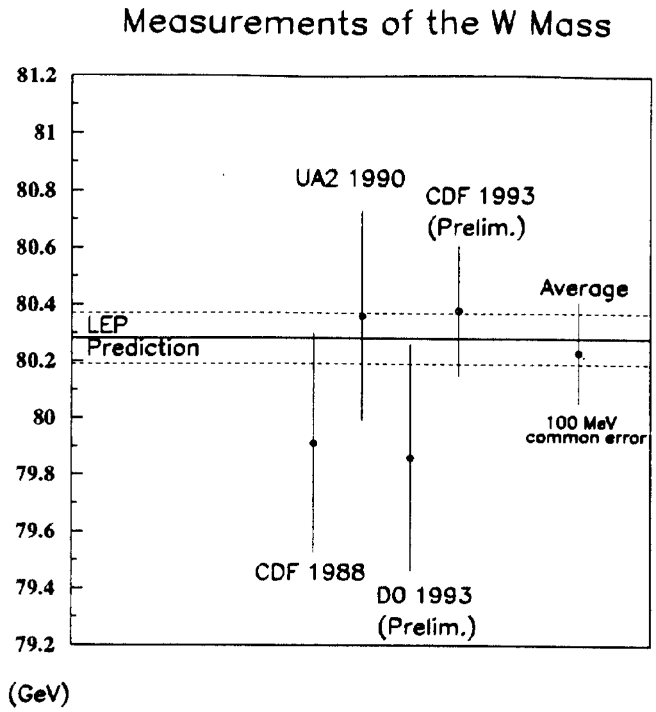

Figure 7: The current measurement of the W mass is compared to measurements from previous or other experiments.

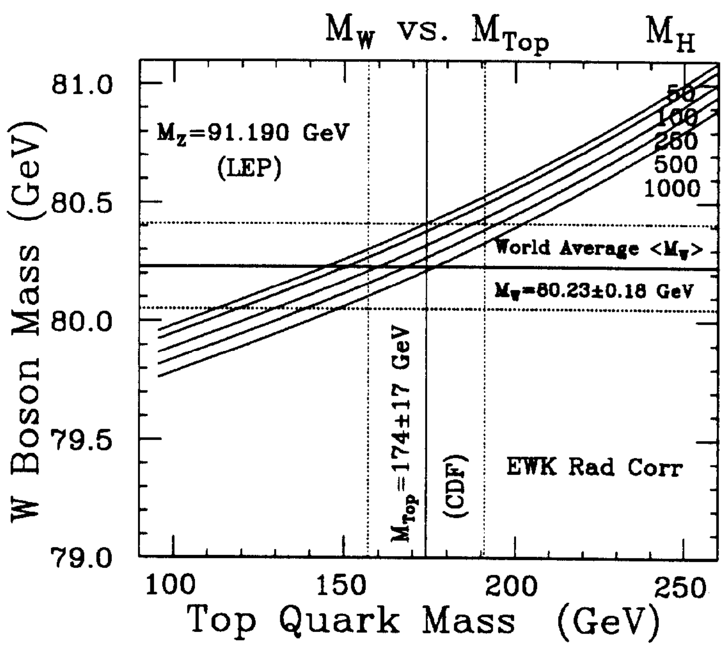

Figure 8: The relation between the W mass and the top quark mass for various values of the Higgs mass. The horizontal lines indicate the combined W mass measurement. and the vertical lines indicate the top quark mass [10].

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