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CDF, D0 and NuTeV

Direct and Indirect Measurements of the W Boson Mass at Fermilab

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DIRECT AND INDIRECT MEASUREMENTS OF THE W BOSON MASS AT FERMILAB

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(for the CDF, DØ and NuTeV Collaborations)

Presented are the direct measurements of the W boson mass from the CDF and DØ experiments at the Fermilab $p\overline{p}$ collider using data from the 1994-1995 run. The W from the DØ experiment is 80.44 $\pm$ 0.12 GeV and the preliminary mass from CDF is 80.43 $\pm$ 0.16 GeV. Combining these mass values with the previous Tevatron measurements leads to a $M_W = 80.41 \pm 0.09$ GeV. Also, presented is the new measurement of $\sin^2 \Theta_W^{on-shell} = 0.2199 \pm 0.0020(stat) \pm 0.0009(syst)$ from the deep inelastic neutrino scattering experiment (NuTeV) at Fermilab. In the context of the Standard Model this can be interpreted as a $M_W = 80.53 \pm 0.11$ GeV.

1 Introduction

A precision measurement of the W boson mass (M_W) is an important test of the Standard Model [1] of electro-weak interactions. In the "on-shell" scheme [2] the W mass may be written as

$$M_W = \left(\frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_w\sqrt{1-\Delta r_W}} \tag{1}$$

where $\alpha(M_Z^2)$ is the electromagnetic coupling constant evaluated at the Z bosons mass (M_Z), G_F is the Fermi coupling constant, $\cos\theta_w \equiv M_W/M_Z$, and Δr_W is due to corrections which depend on the masses of the particles which couple to the W boson. It is through Δr_W that a direct measurement of M_W will constrain the Higgs boson mass or possibly indicate the presence of new physics.

2 Direct W Boson Mass Measurements

Direct measurements of the W boson mass are performed with the CDF and DØ detectors using a 1.8 TeV $p\overline{p}$ beam at the Fermilab Tevatron. The W events used in the analysis are the $W \rightarrow \mu\nu$ decays at CDF [3] and $W \rightarrow e\nu$ decays at DØ [4]. The W bosons are produced mainly through $q\overline{q}$ annihilation. The decay of the W bosons into $l^{\pm}\nu$ states are easily identified by the presence of a high transverse momentum (p_T) charged lepton and significant missing transverse momentum ($\not{p}_T$), due to the neutrino. Since particles are lost down the beam pipe during the $p\overline{p}$ interaction the longitudinal momentum of the W boson cannot be reconstructed. We therefore work in the plane transverse to the beam direction. The W boson mass is extracted from fits to the transverse mass (m_T) and charged lepton p_T distributions. The transverse mass is defined by $m_T = \sqrt{2 p_T \not\!p_T \,(1 - \cos \Delta\phi)}$ where $\Delta\phi$ is the azimuthal angle between the charged lepton and $\not\!p_T$ vectors. The transverse momentum of the W boson is calculated from the charged lepton and missing p_T vectors: $\vec{u}_T = -(\vec{p}_T + \vec{\not\!p}_T)$.

Extracting the mass from the m_T and p_T distributions provides complementary measurements because the transverse mass is less sensitive to the W production process but more sensitive to detector resolutions than the p_T fit. This is illustrated in Fig. 1 using resolutions of the DØ detector. In Fig. 1 the m_T does not change appreciably when the true $p_T(W)$ is added to the system but the $p_T(e)$ distribution is greatly affected. In contrast, when the detector resolutions are included the m_T changes much more than the $p_T(e)$ distribution.

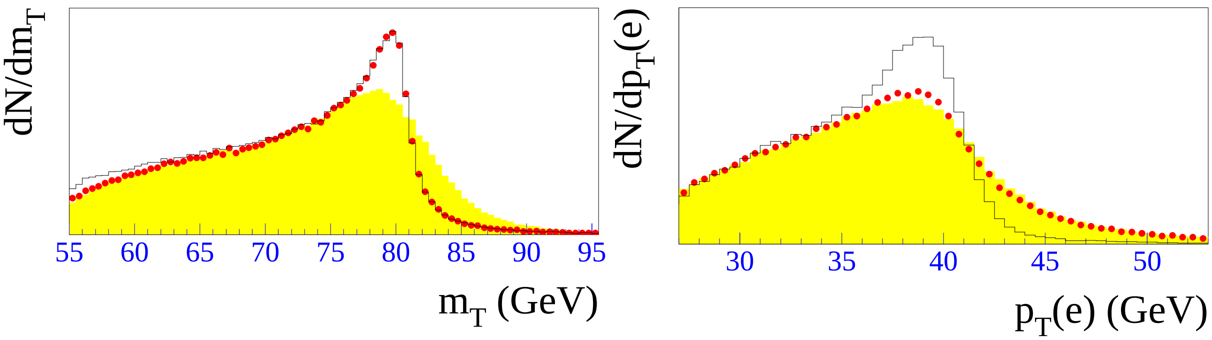

Figure 1: The solid histogram is the m_T (left) and $p_T(e)$ (right) distributions before detector resolutions and with $p_T(W) = 0$. The bullets are when the true $p_T(W)$ is added to the system. The shaded histogram is when the detector resolutions are applied in addition to the true $p_T(W)$.

The m_T or p_T distributions do not have a simple analytical shape therefore a Monte Carlo is used to provide lineshapes as a function of the true W boson mass. A maximum likelihood fit is used to determine the best fit.

2.1 Event Selection

The DØ experiment selects $W \to e\nu$ events from 80pb^{-1} of data by requiring: a high quality isolated electron with $|\eta|<1.0$ and $p_T(e)>25$ GeV, $\not\!p_T>25$ GeV, and $u_T<15$ GeV. With this criteria 28,000 W events are selected, and by requiring a second electron with $p_T(e)>25$ GeV, instead of the $\not\!p_T$ cut, approximately 2,000 Z boson events are selected.

The CDF experiment selects $W \to \mu\nu$ events from 90pb^{-1} of data by requiring: a high quality muon with $|\eta|<1.0$ and $25<p_T(\mu)<60$ GeV, $25<\not\!p_T<60$ GeV, $u_T<20$ GeV, and $50<m_T<110$ GeV. With this criteria 21,000 W events are selected and by requiring a second muon with $25<p_T(\mu)<60$ GeV approximately 1,400 Z boson events are selected.

2.2 Lepton Energy/Momentum Response and Resolutions

The DØ and CDF experiments both calibrate the lepton energy/momentum scale to known resonances [5]. The DØ experiment uses the electromagnetic (EM) decays of the π^0, J/ψ, and Z to measure the response. The functional form of the EM response is known from beam tests to be: $\tilde{E} = \alpha_{EM} \cdot E + \delta_{EM}$ where $\tilde{E}$ is the measured energy, E is the true energy, and α_{EM} and δ_{EM} are constants. Figure 2 shows the 68% confidence level contours in the α_{EM} and δ_{EM} plane for each resonance. The small thick contour, which is expanded in the inset, is the combination of the three contours. The thick arrow indicates the allowed variation due to higher order affects in the EM response.

Once the EM response has been measured the EM resolution is determined from the width of the Z boson mass distribution. The EM resolution is given by $\sigma_{EM}/E = c_{EM} \oplus s_{EM}/\sqrt{E \sin\theta} \oplus n_{EM}/E$ where the noise term (n_{EM}) is take from the W data, the sampling term (s_{EM}) is derived from beam tests, and the constant term (c_{EM}) is derived from the Z data. Figure 2 shows the dielectron mass distribution for the measured EM response and resolution.

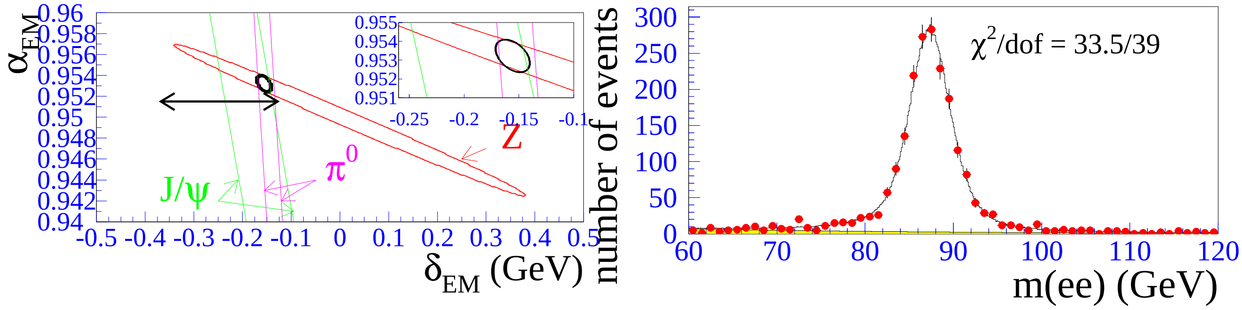

Figure 2: The 68% confidence contours in the EM response parameters from the π^0, J/ψ, and Z data (left). The dielectron mass distribution (right) from which the constant term in the EM energy resolution is determined.

The CDF experiment used the J/ψ, Υ, and Z boson resonances to calibrate the muon momentum. A sample of 250,000 J/ψ events are used to calibrate central tracking chamber. Figure 3 shows the difference between the dimuon mass and the world average J/ψ mass. To study the momentum scale dependence when extrapolating to higher $p_T(\mu)$ values the J/ψ mass is binned in $1/p_T(\mu)$. The $1/p_T(\mu)$ dependence is shown in Fig. 3 along with the Υ and Z mass values recast in terms of the J/ψ mass. An uncertainty is included to cover any trend in $1/p_T(\mu)$. The muon momentum resolution is extracted from the width of the dimuon mass distribution

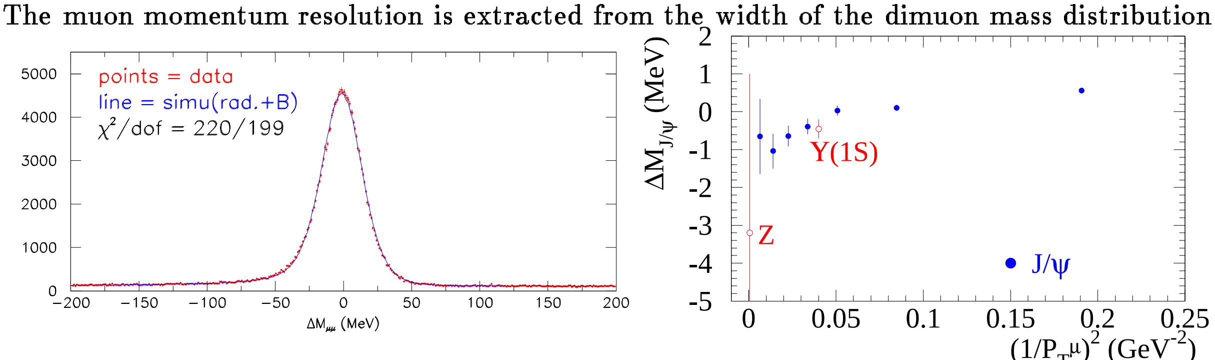

Figure 3: The difference in dimuon invariant mass and the particle data group (PDG) value for the J/ψ mass (left). A plot (right) of the difference of the J/ψ mass and the PDG value as a function of $1/p_T(\mu)$.

of the Z data.

2.3 Hadronic Response and Resolutions

The $\not{\vec{p}}_T$ is determined from the charged lepton momentum and $\vec{u}_T$, where $\vec{u}_T$ is the sum of all the calorimeter cells except those occupied by the charged lepton. The hadronic energy in a W event is assumed to have two components; one 'symmetric' and one asymmetric. The symmetric component is due to the energy flow from the spectator partons from the $p\overline{p}$ interaction, calorimeter noise, and energy from previous interactions. The asymmetric component is due to the initial state gluon radiation which results in a nonzero p_T for the W.

Since the p_T of the Z can be measured from the leptons (p_T^Z) and from the calorimeter (u_T) the response of the hadronic calorimeter is measured with respect to the lepton momentum/energy response. One defines $u_T = \mathcal{R}_{res} p_T^Z$ where $\mathcal{R}_{res}$ is the hadronic response function. In order to minimize the effect of the lepton resolutions the coordinate system is defined where the axis (η) is defined by the angular bisector of the lepton directions in the transverse plane. The second coordinate ξ is at a right angle to η. From Z events the average of $(\vec{p}_T^Z + \vec{u}_T) \cdot \widehat{\eta}$ is plotted versus $\widehat{\eta} \cdot \vec{p}_T^Z$. The slope of this distribution is the hadronic response.

The DØ experiment uses a response function motivated by a study of Z events generated with the ISAJET [6] Monte Carlo and put through a full detector simulation using the GEANT [7] program. The functional form is given by $\mathcal{R}_{res} = \alpha_{res} + \beta_{res} \ln p_T^Z$. This function is used to fit the distribution $(\vec{p}_T^Z + \vec{u}_T) \cdot \hat{\eta}$ versus $\hat{\eta} \cdot \vec{p}_T^Z$ simultaneously for α_{res} and β_{res}.

Once the recoil response has been measured the hadronic resolutions are determined. The width of distribution of $(\vec{p}_T^Z + \vec{u}_T/\mathcal{R}_{res}) \cdot \hat{\eta}$ is a measure of the hadronic resolution. The symmetric component of the hadronic resolution is taken from minimum bias events scaled by a factor α_{mb}. The asymmetric component is parameterized by $s_{rec}\sqrt{u_T}$ and is along $-\vec{p}_T^Z$. A fit is performed to $(\vec{p}_T^Z + \vec{u}_T/\mathcal{R}_{res}) \cdot \hat{\eta}$ in bins of $\hat{\eta} \cdot \vec{p}_T^Z$ for the parameters α_{mb} and s_{rec}.

The CDF experiment determines the hadronic response and resolutions in a similar vein. The hadronic vector u_T is given by $-u_T = (1-\delta)\, p_T^Z + \sigma$. The value of δ is fit to the $(\vec{p}_T^Z + \vec{u}_T) \cdot \hat{\eta}$ distribution of Z events. The components of the hadronic vector p_T^Z are smeared according to their scalar E_T ($\sum E_T$) with resolutions determined from minimum bias data. The resolution parameter σ is taken from Z boson and minimum bias data. The value of σ depends upon the instantaneous luminosity of the event. The instantaneous luminosity is related to the $\sum E_T$ of the event and therefore to the resolutions determined from minimum bias data.

2.4 The Mass Fits

Once the lepton momentum scale, lepton resolutions, hadronic recoil scale, and hadronic recoil resolutions have been measured the W mass can be extracted from the fit to m_T [a].

Table 1: Summary of the errors on the W boson mass measurements from the DØ and CDF experiments in MeV.

	m_T Fit		$p_T(e)$ Fit
	CDF	DØ	DØ
W Statistics	100	70	85
Lepton Energy/Momentum Scale	40	65	65
Total	105	95	105
Calorimeter Linearity	–	20	20
Calorimeter Uniformity	–	10	10
Lepton Energy/Momentum Resolution	25	25	15
Lepton Angle Calibration	–	30	30
Lepton Removal	–	15	15
Selection Bias	10	5	10
Hadronic Recoil Modeling	90	30	20
Input $p_T(W)$ and PDF's	50	25	70
Radiative Decays	20	15	15
Higher Order Corrections	20	–	–
Backgrounds	25	10	20
Fitting	10	–	–
Total Systematics	115	70	90
Total	**155**	**115**	**140**

Figure 4 shows the fit to the m_T distribution from $W \to e\nu$ decays from the DØ detector. The W mass is 80.44 ± 0.07 GeV where the fit has a $\chi^2 = 79.5$ for 60 bins. Figure 4 shows the fit of m_T for $W \to \mu\nu$ decays from the CDF detector. The W mass is 80.43 ± 0.10 GeV where the fit has a $\chi^2 = 62$ for 69 degrees of freedom. Table 1 lists the uncertainties on the W mass due to the various sources for the DØ and CDF measurements.

[a] A precise measurement of the W boson mass involves a number of issues such as backgrounds and efficiencies. For more information see references [3,4,8,9]

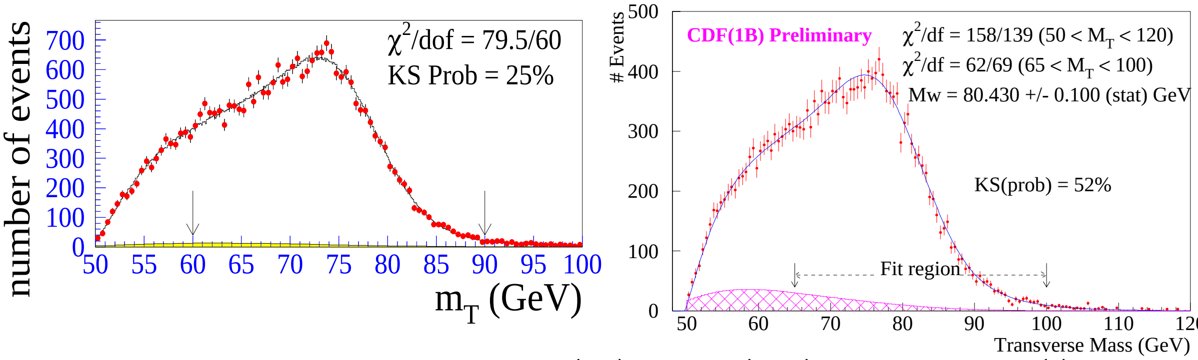

Figure 4: Fits to the m_T distributions from the DØ (left) and CDF (right) collaborations. The (•) are the data, the solid line the Monte Carlo simulation, and the shaded regions the backgrounds.

The fits to the charged lepton p_T distribution yield: for the DØ experiment 80.48 ± 0.09 GeV with a $\chi^2 = 40.6$ for 40 bins and for the CDF experiment 80.51 ± 0.14 GeV with a $\chi^2 = 64$ for 69 bins. We observe that the m_T fits still provide a more precise measurement of the W boson mass than the p_T fits so the W mass values from the m_T fits will be quoted values.

2.5 Combined Result

Combining the DØ result with the W boson mass measurement from the 1992-93 data set [8] yields $M_W = 80.43 \pm 0.11$ GeV. Combining the CDF result with the measurements from 1989 and 1992-93 data set [9] yields $M_W = 80.38 \pm 0.12$ GeV. When these two values are combined, using 50 MeV as a common theoretical error, the Tevatron W boson mass is 80.41 ± 0.09 GeV. Finally including the latest W mass value from LEP II [10], $M_W = 80.35 \pm 0.09$ GeV, we obtain a world average of $M_W = 80.375 \pm 0.065$ GeV.

3 Indirect W Mass Measurement

In the context of the SM a measurement of $\sin^2\Theta_W$ can be evaluated as the W mass through the relation $\sin^2\Theta_W^{on-shell} \equiv 1 - M_W^2/M_Z^2$. Presented is a new precise measurement of $\sin^2\Theta_W$ [11] from the NuTeV experiment at Fermilab. The measurement of $\sin^2\Theta_W$ is performed through deep inelastic muon-neutrino (ν_μ) scattering. The scattering of neutrinos off of nucleon targets may proceed through neutral current (NC), Z in the propagator, or charged current (CC), W in the propagator, interactions. The NC coupling to the quark is proportional to $I_{weak} - \sin^2\Theta_W \times Q_{em}$, where I_{weak} is the weak isospin and Q_{em} is the EM charge. Conversely the CC coupling is proportional to only I_{weak}. Thus, a measure of the neutrino scattering cross sections is a $\sin^2\Theta_W$ measurement. Charged current events are indicated by the presence of a muon which leaves a long trace in the calorimeter and NC are indicated by the absence of a muon. Experimentally the quantity that is least sensitive to systematic errors is the ratio: $R^- = \left(\sigma_{NC}^{\nu_\mu} - \sigma_{NC}^{\bar{\nu}_\mu}\right) / \left(\sigma_{CC}^{\nu_\mu} - \sigma_{CC}^{\bar{\nu}_\mu}\right) = \left(R^{\nu_\mu} - rR^{\bar{\nu}_\mu}\right) / (1 - r)$ [12] where $R^{\nu_\mu} = \sigma_{NC}^{\nu_\mu}/\sigma_{CC}^{\nu_\mu}$ is the ratio of the NC ($\sigma_{NC}^{\nu_\mu}$) to CC ($\sigma_{CC}^{\nu_\mu}$) cross sections for neutrinos, $R^{\bar{\nu}_\mu} = \sigma_{NC}^{\bar{\nu}_\mu}/\sigma_{CC}^{\bar{\nu}_\mu}$ is the ratio of the NC ($\sigma_{NC}^{\bar{\nu}_\mu}$) to CC ($\sigma_{CC}^{\bar{\nu}_\mu}$) cross sections for antineutrinos, and $r = \sigma_{CC}^{\bar{\nu}_\mu}/\sigma_{CC}^{\nu_\mu}$ is the ratio of the CC cross sections for antineutrinos to neutrinos. In terms of $\sin^2\Theta_W$, R^- is equal to $\rho^2\left(1/2 - \sin^2\Theta_W\right)$ where $\rho = 1$ in the SM. The choice of R^- is motivated by the insensitivity to sea quarks limiting the error due to the charm and strange sea quark uncertainties. Measuring R^- requires separate ν_μ and $\bar{\nu}_\mu$ beams to distinguish NC events between ν_μ and $\bar{\nu}_\mu$. The NuTeV collaboration uses a sign selected quadrupole train (SSQT) to select separate ν_μ and $\bar{\nu}_\mu$ beams. The SSQT removes protons and the wrong sign pions and kaons from the beam. The choice of the SSQT has greatly reduced the uncertainty from the ν_e contamination in the beam.

In practice a *pseudo* R^- defined as $R_{20}^{\nu} - xR_{20}^{\bar{\nu}}$ is measured. The subscript 20 refers to the length of the event. The value of x predicted from a Monte Carlo of the detector and beam is ~ 0.484. From the *pseudo* R^- a $\sin^2 \Theta_W^{on-shell} = 0.2199 \pm 0.0020(stat) \pm 0.0009(syst)$ is measured. A more detailed description of the analysis may be found in reference [11]. We note the statistical error is a factor of two larger than the systematic error. Using the relation $M_W = M_Z \sqrt{1 - \sin^2 \Theta_W^{on-shell}}$ and the world average Z mass NuTeV extracts a preliminary W mass of 80.54 ± 0.11GeV. This result is on the same level of precision as the direct measurements.

4 Conclusions

The W mass measurement from the 1989 and 1992-95 data sets at the Fermilab $p\overline{p}$ collider is $M_W = 80.41 \pm 0.09$ GeV. In the future the error will be reduced with the inclusion of the data from the 1994-95 run for the CDF $W \rightarrow e\nu$ data and the DØ $W \rightarrow e\nu$ data in the $1.5 < |\eta| < 2.5$ region. The world average W mass from the combination of the Tevatron and LEP II experiments is $M_W = 80.375 \pm 0.065$ GeV. The latest measurement of $\sin^2 \Theta_W^{on-shell} = 0.2199 \pm 0.0020(stat) \pm 0.0009(syst)$ when evaluated as a measurement of the W mass is $M_W = 80.53 \pm 0.11$ GeV.

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