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DØ and CDF

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Measurement of the W Boson Mass at the Tevatron

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(for the DØ and CDF collaborations)

Presented are measurements of the W boson mass from the DØ and CDF collaborations at the Tevatron from the 1994-1996 run. The W events are produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The W mass extracted from $W \rightarrow e\nu$ decays at DØ is determined to be 80.45 ± 0.12 GeV; and from $W \rightarrow \mu\nu$ decays at CDF is 80.43 ± 0.16 GeV. The world average W mass from the hadron collider measurements is 80.41 ± 0.09 GeV.

1. Introduction

The W boson mass is given, at lowest order, in terms of the electromagnetic coupling constant (α), the Fermi constant (G_F), and the Z boson mass (M_Z) by equation 1

$$M_W = \left(\frac{\pi\alpha (M_Z^2)}{\sqrt{2}G_F} \right)^{\frac{1}{2}} \frac{1}{\sin\theta_W \sqrt{1-\Delta R}} \quad (1)$$

where $\cos\theta_W = \frac{M_W}{M_Z}$ and at lowest order ΔR is zero. At higher orders of perturbation theory ΔR depends upon the masses of the particles in the W self energy diagrams. Thus, in the context of the Standard Model [1] a precise measurement of the top quark mass and M_W provides a constraint on the unobserved Higgs particle mass. Likewise, in the event of new particles, ΔR is modified by the masses of these particles. Therefore, a precise measurement of M_W provides a constraint on new physics [2].

2. Overview

In $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV the W events are mainly produced through quark-antiquark annihilation. The initial momentum of the $p\bar{p}$ system in the transverse plane is approximately zero. Therefore, the sum of the momentum in the transverse plane after the W is produced and decays is also zero. The W events used to measure the mass are only the events which decayed into leptons ($e\nu, \mu\nu$). Thus, any momentum imbalance

in the transverse plane is attributed to the neutrino. The longitudinal component of the neutrinos momentum cannot be determined because of the particles not observed along the beam line.

The W mass is extracted from a fit to the kinematic distribution of its decay products. For this paper the mass is extracted from a fit to the transverse mass (m_T). The transverse mass is given by equation 2

$$m_T = \sqrt{2p_T^l \cancel{p}_T (1 - \cos\phi)} \quad (2)$$

where p_T^l is the charged lepton ($l = e, \mu$) transverse energy (momentum), \cancel{p}_T is the missing transverse momentum, and ϕ is the angle between p_T^l and \cancel{p}_T in the transverse plane. In practice what is measured is the angle and energy (momentum) of the charged lepton (\vec{p}_T^l) and \vec{u}_T , which is the vectorial sum of all the energies in the transverse plane except for \vec{p}_T^l . The missing transverse momentum is given by $\cancel{p}_T = -(\vec{u}_T + \vec{p}_T^l)$ and is attributed to the neutrino.

The m_T does not have a simple analytical form and therefore a fast Monte Carlo is used to provide m_T lineshapes as a function of the hypothesized W mass. The fast Monte Carlo can be divided into two parts: the theory section and the detector simulation. The theory portion involves the production and decays of the W . The initial p_T of the W , due to gluon radiation, is given by the calculation in reference [3]. Also included are the decay of the W to leptons ($W \rightarrow l\nu$) [4], radiative decays ($W \rightarrow l\nu\gamma$) [5], and the indistin-

guishable background($W \rightarrow \tau\nu \rightarrow l\nu\nu\nu$).

The shape of the m_T distribution is affected by the detector resolutions. The resolutions in the fast Monte Carlo are taken directly from data and will be discussed in sections 4 and 5.

This paper presents measurements of the W mass from $D\emptyset$ [6] based on $W \rightarrow e\nu$ decays and from CDF [7] based in $W \rightarrow \mu\nu$ decays.

3. Event Selection

The event selection for both analyses are quite similar. Both require that $p_T^l > 25$ GeV, $\cancel{p}_T > 25$ GeV and $|\eta| < 1.0$. Each analysis has a series of quality cuts on the charged lepton that improve the signal and remove backgrounds. $D\emptyset$ requires $u_T < 15$ GeV where CDF has a cut of 20 GeV. Based on 76 pb^{-1} of data $D\emptyset$ obtains $\sim 28,000$ W and $\sim 2,200$ Z events, and with 90 pb^{-1} of data CDF has $\sim 21,000$ W and $\sim 1,400$ Z events.

4. Charged Lepton

One can see from equation 2 that in order to model m_T properly one needs to measure the momentum of the charged lepton(e, μ) to a very high precision. Similarly the resolution of the lepton momentum has to be known in order to model the observed m_T spectrum.

4.1. $D\emptyset$

The energy of an electron¹ is measured using the uranium-liquid argon calorimeter of the $D\emptyset$ detector. The functional form the energy response has been measured at a test beam to be: $\vec{E} = \alpha \cdot E + \delta$ where \vec{E} is the measured energy, E is the true energy, and α and δ are constants. The electromagnetic decays of the π^0 and J/ψ are used to constrain δ and the Z resonance is used to measure α . The error on the W mass due to the uncertainty on the electromagnetic energy scale is 65 MeV and is dominated by the statistical error on the Z .

The width of the Z resonance is used to measure the energy resolution of the electrons. Since

¹The $D\emptyset$ detector does not have a central magnetic field and therefore electrons and positrons will be generically referred to as electrons.

the natural width of the Z is so precisely determined any additional resolution on the mass is due to the resolution of the leptons. The error on the W mass due to the uncertainty in the electromagnetic energy resolution is 20 MeV.

4.2. CDF

The momentum scale of the muons is set using $J/\psi \rightarrow \mu\mu$ decays. A sample of $\sim 250\text{k}$ events is used to calibrate the central tracking chamber. The simulation of the J/ψ lineshape includes the effects of B decays and QED corrections.

The momentum scale calibration needs to be transferred from the low p_T muons from the J/ψ events to the high p_T muons from the W decays. To this end the mass of the dimuon sample is binned in $1/p_T$. A systematic error is assigned to accommodate a slight dependence in $1/p_T$. A cross check using the Υ resonances and Z mass is shown to be consistent within the errors. The error on the W mass due to the uncertainty on the momentum scale is 40 MeV.

5. Hadronic Recoil

The \cancel{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 a symmetric and asymmetric component. The symmetric component is due to the energy flow from the spectator partons in the interaction, calorimeter noise, and energy from previous interactions. The asymmetric component is due to the gluon radiation which results in a nonzero p_T for the W .

5.1. Hadronic Recoil Response

Since the p_T of the Z can be measured from the leptons (p_T^Z) directly and from the calorimeter (u_T) one can use this to study u_T . In this way 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 a coordinate system is defined for which an axis (η) is given by the angular bisector of the lepton directions in the transverse plane. The sec-

ond coordinate ξ is at a right angle to η . From Z events the average of $(\vec{p}_T^Z + \vec{u}_T) \cdot \hat{\eta}$ is plotted versus $\hat{\eta} \cdot \vec{p}_T^Z$. The slope of this distribution is the hadronic response.

5.1.1. $D\bar{O}$

The response function used is motivated by a study of Z events generated with the ISAJET [9] Monte Carlo and put through a full detector simulation using the GEANT [10] 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} . The fitted values are $\alpha_{res} = 0.69 \pm 0.06$ and $\beta_{res} = 0.04 \pm 0.02$ with a correlation coefficient of $\rho = -0.979$.

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 fit has a $\chi^2 = 10.3$ for 8 degrees and we find $s_{rec} = 49 \pm 14\%$ and $\alpha_{mb} = 1.032 \pm 0.028$ with a correlation coefficient of $\rho = -0.60$. A correction to α_{mb} of 1.03 ± 0.03 is made for energy flow differences between Z and W samples used in the analysis. The error on the W mass due to the uncertainty on the hadronic response and resolution is 40 MeV.

5.1.2. CDF

In a similar vein the hadronic response and resolutions are determined for $W \rightarrow \mu\nu$ data. The hadronic vector u_T is given by $-u_T = (1 - \delta) \vec{p}_T^Z + \sigma$. The value of δ is measured from the η -balance of Z events. The components of the hadronic vector \vec{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 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. The error on the W mass due to the uncertainty on the hadronic response and resolution is 90 MeV.

6. The W Mass

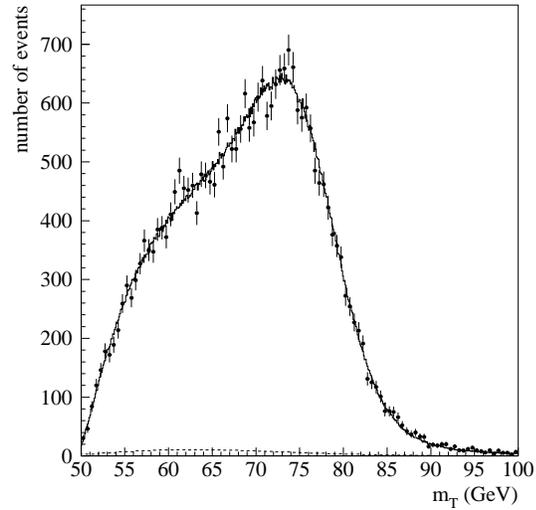


Figure 1. A fit to the m_T distribution of data (\bullet) from the $D\bar{O}$ detector, the Monte Carlo simulation (—), and backgrounds (- -).

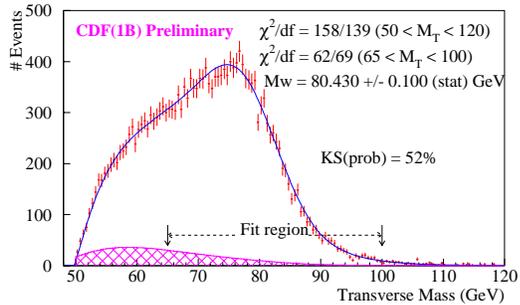


Figure 2. A fit to the m_T distribution of data (\bullet) from the CDF detector, the Monte Carlo simulation (—), and backgrounds (hatched).

Once the lepton momentum scale, the lepton resolutions, the hadronic recoil scale and resolutions have been measured the W mass can be

extracted from the fit to m_T^2 .

Figure 1 shows the fit to the m_T distribution from $W \rightarrow e\nu$ decays from the DØ detector. The W mass is 80.45 ± 0.07 GeV where the fit has a $\chi^2 = 77$ for 59 degrees of freedom. Figure 2 shows the fit of m_T for $W \rightarrow \mu\nu$ 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.

Table 1
A summary of the uncertainties for the DØ and CDF measurements. The units are in MeV.

	DØ	CDF
W Statistics	70	100
Lepton Scale	65	40
Calorimeter Linearity	20	–
Lepton Resolution	20	25
Recoil Modeling	40	90
Input p_T^W , PDF's	25	50
Radiative Decays	20	20
Higher Order Cor.	–	20
Backgrounds	10	25
Angle Calibration	30	–
Fitting	–	10
Miscellaneous	20	20
Total Systematics	70	115
Total	120	155

6.1. Combined Results

Combining these W mass values with the previous measurements [11–13] from hadron colliders yields a W mass of 80.41 ± 0.09 GeV where 50 MeV has been used as the common uncertainty.

²For an accurate measurement of the W mass a number of issues such as backgrounds and efficiencies have to be addressed. For more information on this subject see references [6,7]

7. Conclusions

The measurements of the W boson mass from the DØ and CDF collaborations at the Tevatron are presented. The combined W mass from the hadron collider experiments is 80.41 ± 0.09 GeV. Using equation 1 one finds $\Delta R = -0.0276 \pm 0.0058$ which corresponds to a 4.7σ deviation from the LO prediction.

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