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W Mass and W Asymmetry at CDF*

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ABSTRACT

The lepton charge asymmetry from W decaying into a lepton and a neutrino is discussed (preliminary result). This measurement gives information on parton distribution functions at low x values. The derivation of the recently published W mass value of 79.91 ± 0.39 GeV/c^2 is also presented. M_W is used to set an upper limit on the top quark mass.

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1. INTRODUCTION

CDF (Collider Detector at Fermilab) is a multipurpose detector, built to study proton-antiproton interactions at the Fermilab Tevatron Collider, at a center of mass energy of 1.8 TeV. During its first high luminosity run in 1989-1990, the Tevatron reached a peak luminosity of 2×10^{30} cm^{-2} sec^{-1}. CDF collected data for an integrated luminosity of 4.4 pb^{-1}.

Among many interesting data samples, the run yielded several thousand W's decaying into a charged lepton and a neutrino. The high quality of this sample enabled CDF to make measurements of several electro-weak parameters. Here we will concentrate on the measurements of the W mass and of the lepton charge asymmetry from W decay. The masses m(W) and m(Z) of the vector bosons are fundamental parameters in the Standard Model. Together, they determine the weak mixing angle. When this experimental value of $\sin^2\theta_W$ is compared with the value obtained in charged current and neutral current experiments at low momentum transfers, one can derive limits on the mass of the yet unobserved top quark. The lepton asymmetry measurement allows one to investigate the W production mechanism. It also gives information on the proton parton distribution functions. The measurements are made using both electron and muon decay channels.

The CDF detector have been described in detail elsewhere[1)].

2. LEPTON CHARGE ASYMMETRY FROM W DECAY

2.1 Basic concepts and predictions.

At $\sqrt{s} = 1.8$ TeV, W's are produced at very low x (x is the parton momentum fraction relative to the beam momentum) and high Q^2. More than 85 % of the W's are expected to be created by valence-sea or valence-valence quark-antiquark interactions[2)], the former giving the dominant contribution. A W^+ will be produced primarily by the interaction of a u quark from the proton and a d-bar quark from the antiproton. Because u quarks in the proton have, on average, higher momentum than d quarks, a W^+ will tend to be boosted along the proton beam direction, and conversely a W^- will be boosted along the anti-proton direction. A measurement of the W rapidity distribution in a p-pbar collider would therefore give information about parton distribution functions at those values of x and Q^2 where W's and Z's are produced. These investigations are interesting in their own right. In addition, the understanding of the parton distribution functions is important for other measurements, such as an accurate W mass measurement and a measurement of the ratio $R = \sigma (W) / \sigma (Z)$.

There is a problem however: at the high energy of the Tevatron we cannot reconstruct the W rapidity (Y_W) distribution, because we cannot measure the longitudinal momentum of neutrinos coming from W decay. At the SPS collider this problem was solved by imposing the value of the W mass on the charged lepton - missing transverse energy system. After doing this, one found two solutions for the neutrino four-momentum. At $\sqrt{s} = 630$ GeV, the solution which minimizes $| Y_w |$ was the right one in most cases. At the Tevatron, the W's have a large longitudinal boost which makes the wrong solution equally likely in the central region of the detector. However, the W rapidity has a strong influence on the rapidity distribution of the decay leptons, which also depends on the V - A couplings. Therefore we investigate the lepton (pseudo) rapidity as a means to study structure functions at low x. It is convenient to measure the charge asymmetry of the leptons as a function of rapidity:

$$A(|\eta|) = \frac{N^+ - N^-}{N^+ + N^-}$$

where N^+ is taken to be the number of events with charge(lepton) x rapidity(lepton) > 0 and N^- vice-versa[3]. This asymmetry is insensitive to acceptance corrections, requiring only equal detection efficiency for both lepton charges and small corrections for background events.

Fig. 1 shows the lepton asymmetry, $A(|\eta|)$, computed at lowest order for different sets of structure functions[6,7,8,9]. The effect of higher-order QCD diagrams for W production was investigated with the Papageno Montecarlo by producing several million W events with either 1 or 0 jets, using EHLQ1, MRS1 and DO1 structure function sets. The asymmetry in the central region is predicted to increase with increasing the transverse momentum of the W. For our analysis we will use low Pt W's only. For the range of Pt(W) of interest here, we estimate the size of this increase in asymmetry due to the non-zero Pt of the accepted W's to be less than 0.01[3].

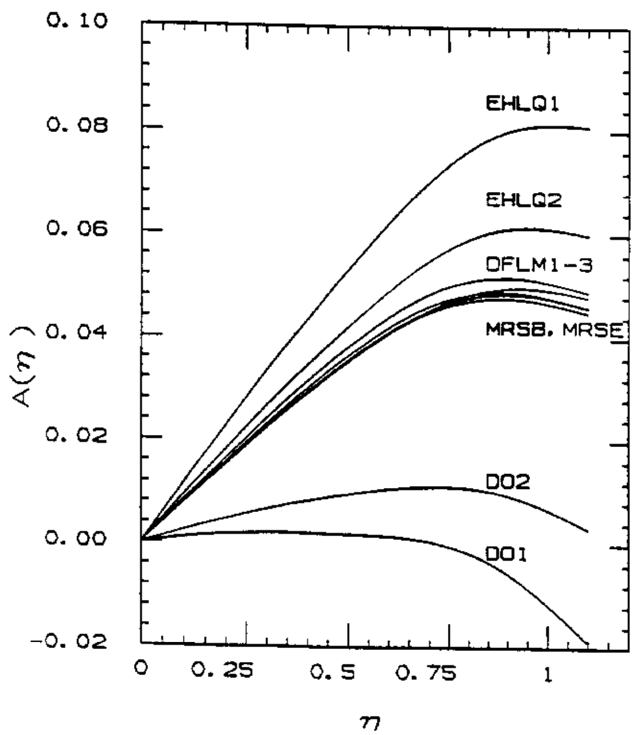

Fig. 1 Lepton charge asymmetry in W decay obtained from several structure functions.

2.2 Event selection and results.

W and Z decays are the primary source of charged leptons with transverse momenta above 20 GeV/c. The neutrino from W decay escapes detection, producing an apparent transverse energy flow imbalance. We isolate W decays by looking for events with high transverse momentum electrons or muons and large missing transverse energy.

We use three types of W events, denoted by the lepton type and the calorimeter section into which the lepton traveled: central electrons[4)], central muons[3)] and plug electrons[5)]. Trigger requirements are as follows. Central electron events must have at least one calorimeter cluster with EM transverse energy above 12 GeV, a ratio of hadronic to electromagnetic calorimeter energy HAD/EM < 0.125 and a track pointing to the cluster with transverse momentum Pt > 6 GeV/c. Central muon events contain a track with Pt > 9.2 GeV/c pointing to a central muon chamber segment (called 'stub'). Plug electron events contain either a plug calorimeter cluster with EM transverse energy > 23 GeV and HAD / EM < 0.125 or missing transverse energy > 25 GeV, with the most energetic calorimeter cluster having EM transverse energy > 8 GeV. We do not go here into the details of the offline event selection, which can be found in references[3,4,5)]. However, events having isolated, the fundamental physical requirements for the central leptons are:

- Pt (lepton) > 20 GeV/c
- Mt(lepton-neutrino) > 50 GeV/c^2
- No Jets with Et > 10 GeV.
- Isolation.

For the plug electrons we required:

- Mt(lepton-neutrino) > 60 GeV/c^2.

We applied specific quality cuts on the three samples (i.e. shower quality requirements for the electrons, good match between extrapolated Central Tracking Chamber tracks and Central Muon Chamber 'stubs' for muons etc.). We subtracted possible fake W's generated by misidentified Z's in the muon sample, and rejected cosmic ray candidates.

After all cuts, the final sample contains 1651 central electron events, 800 central muon events and 262 plug electron events. These samples are quite clean: it is estimated that the possible background would affect the asymmetry by less than 1%. Several studies have been performed to verify that the detection efficiency is the same for both lepton charges. They all showed charge independence at the level of 1%.

In Fig. 2 we show the measured asymmetries. The plug electron data, at $|\eta| = 1.5$ is compaired to a different set of curves, because this sample was selected with a higher transverse mass cut. The muon measurement is limited in η at 0.7 by the detector acceptance. All sets of parton distribution functions except for DO1 and DO2 are in satisfactory agreement with our data. The uncertainty in our measurement is dominated by statistics.

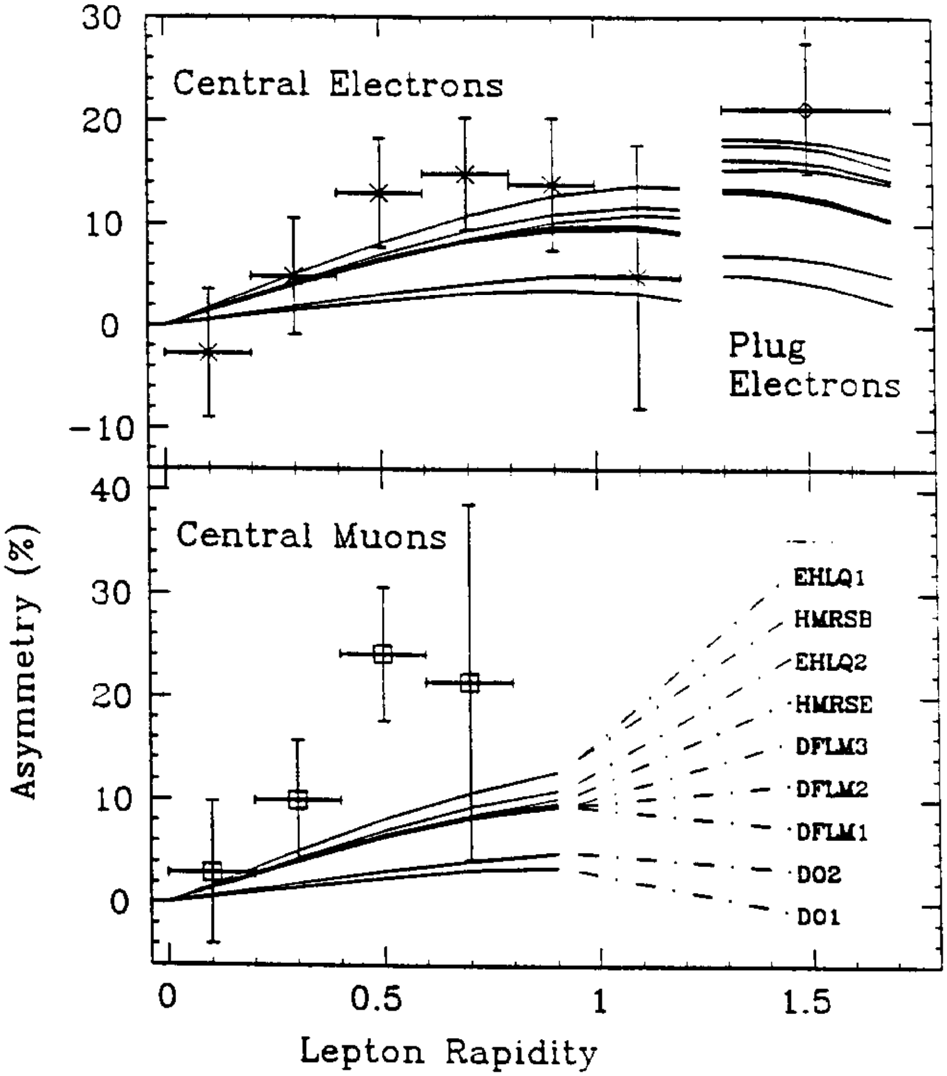

Fig. 2 Lepton asymmetries in W events, compared to predictions of leading-order calculations for various parton distributions.

2. W MASS MEASUREMENT

2.1 Basic concepts.

The W decay W -> l ν is a two body decay. For a W decaying at rest the transverse momentum spectrum of the leptons peaks at half the mass of the W. Experimentally the picture is more complicated. The W is not produced at rest, neither in the longitudinal (along the beam) nor in the transverse direction. The transverse momentum of the W, P_T^W, smears the electron momentum distribution. The longitudinal momentum of the W contributes to the longitudinal momentum of the electron. Due to these effects, electrons emitted at a given angle are not monochromatic. Furthermore, we cannot directly reconstruct the invariant mass of the two leptons (i.e. as we do with Z's) because of the undetected neutrino. We determine the transverse momentum of the neutrino from conservation of the total transverse momentum in the event. The transverse mass is defined as follows:

$$m_T = [\ 2\ p_T^l\ p_T^\nu\ (\ 1 - \cos \phi_{l\nu}\ )\ ]^{1/2}$$

where $\phi_{\nu l}$ is the difference in azimuth ϕ between the charged-lepton and the neutrino direction. We get the W mass comparing the measured transverse mass distribution to that predicted by Montecarlo[10].

3.2 Event selection.

For this measurement we used central leptons only. The event selection at the trigger level was the same as described in the previous section. Offline, we required also:

- Pt(lepton) > 25 GeV/c
- Pt(neutrino) > 25 GeV/c
- No Jets with Et > 7 GeV.

We also applied fiducial cuts, in order to use only the most efficient region of our detector. We applied quality cuts on technical variables. We rejected cosmic rays and misidentified Z's faking W's from the muon sample, and removed conversion electrons from the electron sample. The final sample contains 1130 central electron events and 592 central muon events.

3.3 W mass fit and Montecarlo model.

The W mass is obtained from a maximum-likelihood fit of the experimental transverse mass distributions to those of Montecarlo predictions, obtained with different input masses. The Montecarlo program includes the physics of W production and decay as well as a simulation of detector response for both the charged lepton and the underlying hadronic event from which the neutrino momentum is derived. Uncertainties in these quantities lead to systematic uncertainties in the W mass. We included in the Montecarlo model sufficient degrees of freedom to reflect these uncertainties. For the final evaluation of the W mass, the W width was constrained to $\Gamma = 2.1$ GeV, the value predicted by the Standard Model. This is important otherwise one observes significant mass-width correlations (due to the finite detector resolution). Fig. 3 shows the observed and fitted transverse mass distributions. The fitted range is 65 - 94 GeV/c^2. The results, corrected for radiative effects, are[10]:

$$m_W^e = 79.91 \pm 0.35\ (\text{stat}) \pm 0.24\ (\text{syst}) \pm 0.19\ (\text{scale})\ \text{GeV}/c^2$$

$$m_W^\mu = 79.90 \pm 0.53\ (\text{stat}) \pm 0.32\ (\text{syst}) \pm 0.08\ (\text{scale})\ \text{GeV}/c^2.$$

The combined result is:

$$m_W = 79.91 \pm 0.39 \text{ GeV}/c^2.$$

This is consistent with previous measurements. In Table 1 we show the uncertainties in the W mass measurement. All uncertainties are quoted in units of MeV/c^2. In parenthesis are the statistical (and overall) uncertainties if Γ_W is determined in the fit as well. The energy scale of the calorimeter is calibrated using the magnetic spectrometer to measure the momentum of electrons[11]. As a check of our measurement, we also fit the lepton P_T spectra. The results were consistent with the m_T fits.

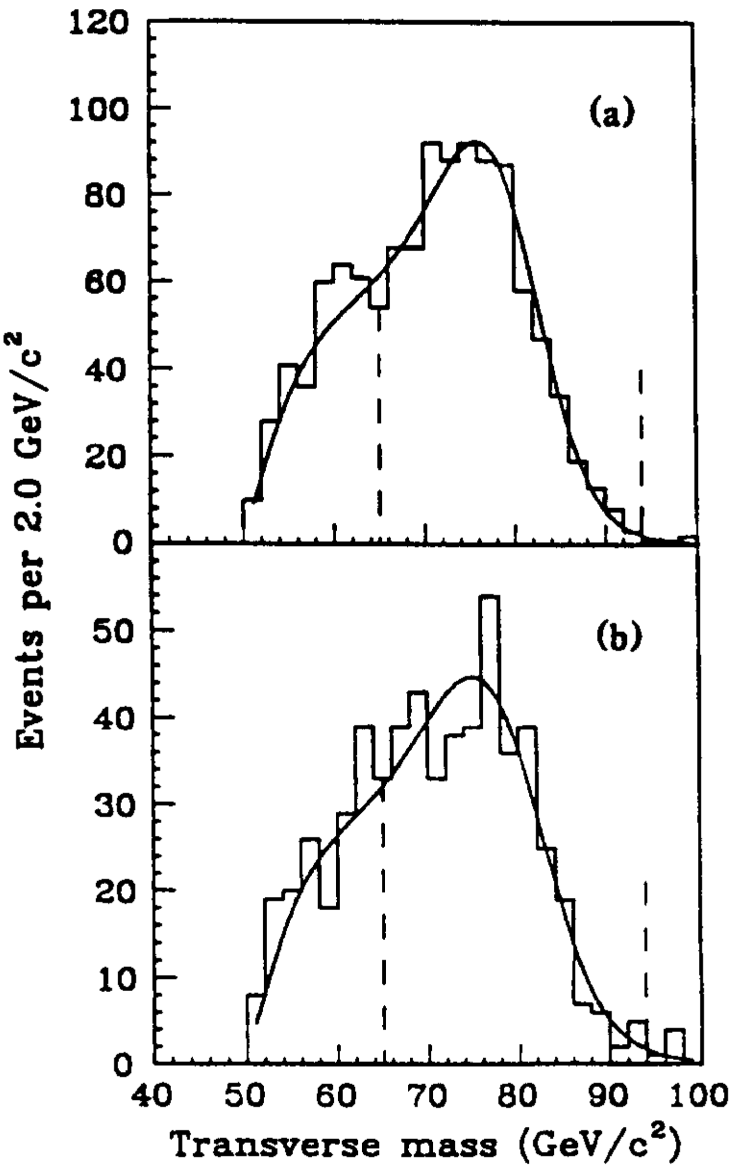

Fig. 3 (a) The transverse mass distribution for W -> e ν candidates. (b) The transverse mass distribution for W -> μν candidates. Overlaid is the best fit to the data.

In order to determine the weak mixing angle, we combined the W mass values from the electron and muon decays with the world-average Z mass[12] of 91.161 ± 0.031 GeV/c^2, obtaining:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} = 0.2317 \pm 0.0075.$$

Fig. 4 shows the expected relationship between the top-quark mass and $\sin^2\theta_W$. For a Higgs-boson mass lighter than 1000 GeV/c^2 the top-quark mass is constrained, within the Minimal Standard Model, to be $m_{top} < 220$ GeV/c^2 (95 % C.L.). The 89 GeV/c^2 lower top mass limit (95 % C.L.) is from CDF[13]. The curves, from top to bottom, correspond to Higgs boson masses of 1000, 250 and 50 GeV/c^2.

UNCERTAINTY	ELECTRONS	MUONS	COMMON
Statistical	350 (440)	530 (650)	
Energy scale	190	80	80
(1) Tracking chamber	80	80	80
(2) Calorimeter	175		
Systematics	240	315	150
(1) Proton Structure	60	60	60
(2) Resolution, Pt (W)	145	150	130
(3) Parallel Balance	170	240	
(4) Background	50	110	
(5) Fitting	50	50	50
OVERALL	465 (540)	620 (725)	

Table 1 Uncertainties in the W mass measurement. Those parts of uncertainties which are the same for both samples are listed in common.More details on the systematic uncertainties can be found in reference [11].

4. CONCLUSIONS

The most important parameter of the EWK theory supplied by the hadron colliders is the mass of the W. CDF has made a precision measurement of the W boson mass. Thanks to the energy scale calibration provided by the central magnetic spectrometer, the achieved precision is remarkable and the measurement uncertainties are so far limited by the statistics of the data sample. In the near future, the Tevatron will be the best place to observe W's and study their properties. CDF hopes to collect 50 pb^{-1} of data during the next run. The already satisfying performance of the CDF detector will be further improved by various upgrading programs. This will reduce both the statistical and systematic error on the W mass. This will also allow an improved measurement of the W charge asymmetry (we expect a reduction of the statistical error by a factor of three in the next run). It is hoped that eventually such asymmetry measurement can contribute valuable information to be input to the overall data-fit which shall determine the proton structure functions.

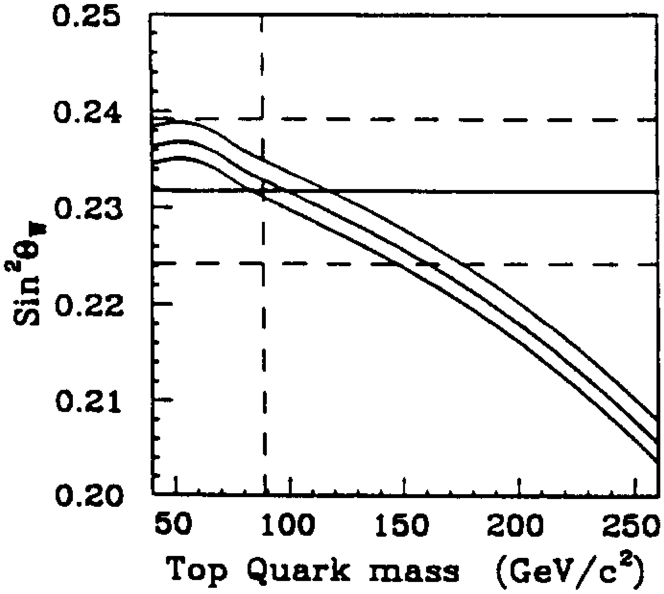

Fig. 4 $\sin^2\theta_W$ as function of the quark top mass.

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