Fermi National Accelerator Laboratory

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CDF Measurements of the W Mass and Search for the Top

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CDF Measurements of the W Mass and Search for the Top

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The derivation of the W mass value of 79.91±0.39 GeV/c² is discussed. The present limit at 91 GeV/c² (95 % C.L.) on the mass of the top quark is also presented. In the next two years of data collection, we expect to collect significantly more luminosity than in the past. We discuss prospects for the discovery of the top quark and improvements of the current measurements.

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 x 10^{30} $cm^{-2}sec^{-1}$. CDF collected data for an integrated luminosity of 4.4 pb^{-1}. Here we will concentrate on the measurements of the W mass and on the search for the last missing quark: the top. 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. Combining the W mass value with the top mass value one can test the Standard Model and put a constraint on the mass of the Higgs. These two measurements are among the most interesting ones which can be performed at a hadron collider.

The CDF detector has been described elsewhere(1).

2. W MASS MEASUREMENT

The W decay $W \to l\ \nu$ is a two body decay. For a W decaying at rest the transverse momentum spectrum of the leptons peaks at half of the mass of the W. At the Collider 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:

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

where $\phi_{l\nu}$ 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 Montecarlo predictions (2,3).

2.1. Event selection

For this measurement we used central leptons only, i.e. those that go through the scintillator calorimeters, at pseudorapidity $|\eta| < 1.0$ for electrons and $|\eta| < 0.6$ for muons. To trigger, central electron events are requested to have at least one calorimeter cluster with EM transverse energy above 12 GeV, a ratio of hadronic to electromagnetic energy HAD/EM < 0.125 and a track

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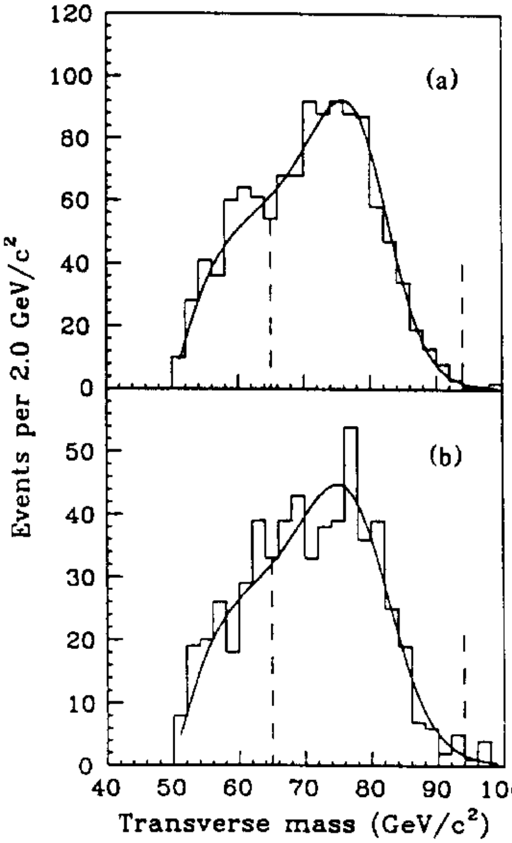

Figure 1: (a)The transverse mass distribution for W $\rightarrow e\nu$ candidates. (b) The transverse mass distribution for W $\rightarrow \mu\nu$ candidates. Overlaid is the best fit to the data.

pointing to the cluster with transverse momentum $P_T > 6$ GeV/c. Central muon events must contain a track with $P_T > 9.2$ GeV/c pointing at a central muon chamber segment. We do not go here into the details of the offline event selection, which can be found in references [2,3]. However, the fundamental physical requirements for the central leptons are:

- P_T(lepton) > 25 GeV/c
- Event Missing $E_T > 25$ GeV/c
- No central jets with $E_T > 7$ GeV.

We applied specific quality cuts on other variables defining the quality of the tracks. We also applied fiducial cuts, in order to use only the most efficient region of our detector. We rejected cosmic rays and misidentified Z's faking W's from the muon sample, and removed conversion electrons from the electron sample.

After all cuts, the final sample contains 1130 central electron events and 592 central muon events.

2.2. W mass fit and Montecarlo model.

The W mass is obtained from a maximum-likelihood fit of the experimental transverse mass distribution 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 the detector response for both the charged lepton and the underlaying 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. Fitted values of m_W and Γ_W are correlated. 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.

Figure 1 shows the observed and fitted transverse mass distributions. The fitted range is 65 - 94 GeV/c^2. The results, corrected for radiative effects, are [2,3]:

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

and

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

The combined result is:

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

In Table 1 we show the uncertainties (units of MeV/c^2) in the W mass measurement. In parenthesis are the statistical (and overall) uncertainties if Γ_W as well as m_W is determined in the fit. The energy scale of the calorimeter is calibrated using the magnetic spectrometer to measure the momentum of electrons [3]. As a check of our measurement, we also fit the lepton P_T spectra. The results are consistent with the m_T fits.

UNCERTAINTY	ELECTRONS	MUONS	COMMON
Statistical	350(440)	530(650)	
Energy scale	190	80	80
1) CTC	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 [3].

3. SEARCH FOR THE TOP

The search for the sixth quark has been and still is the "top" priority search for the $p\bar{p}$ collider experiments. For masses $m_{top} \geq m_W$, top quarks are expected to be produced at the Tevatron via the process $p\bar{p} \rightarrow t\bar{t} + X$ [4,5] (fig. 2). In the framework of the Standard Model each top quark is expected to decay into a W boson and a b quark ($t \rightarrow Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. Thus, the $t\bar{t} \rightarrow W^+bW^-\bar{b}$ events have a several different signatures involving combinations of several energetic leptons or quark jets.

CDF can search for the top quark using most of these signatures. The efficiency of each signature varies as a function of m_{top} so that, as we look for higher top quark masses, different signatures become more effective.

The branching ratio for both W's from a $t\bar{t}$ pair to decay leptonically is: 2/81 for $e\mu$, $e\tau$, $\mu\tau$ and 1/81 for ee, $\mu\mu$, $\tau\tau$. τ's have not been used until now for top search.

The cleanest signature for the production and decay of a $t\bar{t}$ pair is the presence of two high P_T(e or μ) leptons in the final state.

Decay modes of $t\bar{t}$ pairs in which one of the W boson decays hadronically and the other leptonically have a comparetively large branching ratio (24/81), but in these channels there is an important background from directly produced W boson in association with jets. This background can be reduced by using the information from the topology of the event and by tagging the b quark.

Decay modes of $t\bar{t}$ pairs in which both W's decay hadronically have the largest branching fraction (36/81), but are difficult to distinguish from multijet QCD background.

3.1. Single lepton channel.

CDF obtained a limit on m_{top} by analyzing a sample of W + 2 jet candidate events[6]. If $m_{top} < m_W$, the W produced in the top decay is virtual. In that case the transverse mass distribution of W's is different for top events and for real (on shell) W events. The off-line requirements were:

- E_T(el) > 20 GeV
- E_T^m > 20 GeV
- At least two jets, with E_T(jet) > 10 GeV
- $m_T^{e\nu}$ > 40 GeV.

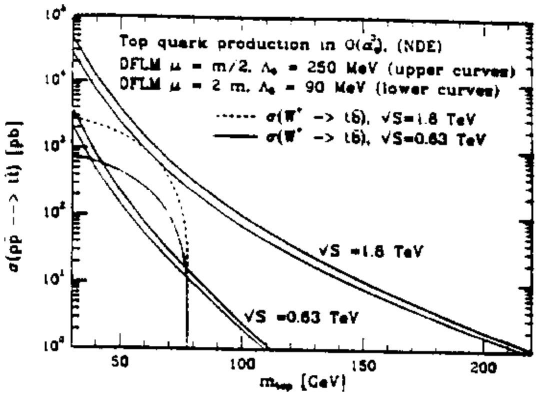

Figure 2: Top production cross section as a function of the top mass.

The data were in good agreement with being due to real W's only. The limit obtained was $m_{top} > 77 GeV/c^2$ (95% C.L.).

This analysis looses its selection power for $m_{top} > m_W + m_b$ since the W in top decay becomes real. In order to extend the analysis to higher values of the top mass new strategies must be developed. There should be differences in the event structure between top and background events[7]. Variables which can be studied are for example E_T(jet), $\Delta\phi$(jet-jet) or $\mathrm{Cos}\Theta^*$(jet) (Θ^* being the CMS angle of the jets). In order to study these possible differences we need to quantitatively understand Montecarlo predictions for top and for QCD W+jet events. Reliable estimates of the size of the W+jets background to a heavy top are difficult to make, due to the fact that the background results from higher-order QCD diagrams which are difficult to calculate.

As an example of the work done to understand the background, we show here a comparison between data and Montecarlo for W + 3 jet events. The details of the analysis can be found in ref.[7]. The Montecarlo used was Vecbos [8]. Vecbos can produce W + n jet events, n=1,2,3,4. It uses the correct matrix elements to lowest order. In figure 3 (a) and (b) we show respectively a comparison for the E_T(third jet) and for the $\mathrm{Cos}\Theta^*$(third

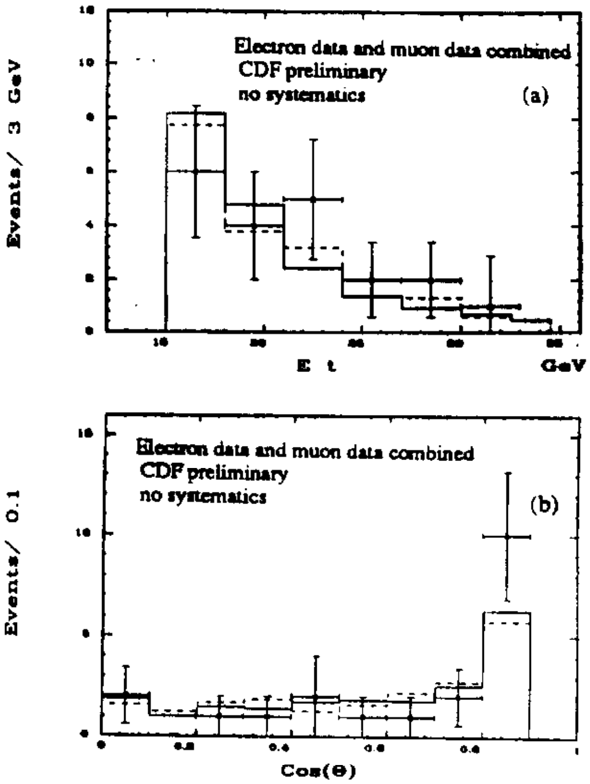

Figure 3: Comparison Vecbos-data for W+3 jets.

jet) spectra.

The background was not subtracted and the systematic uncertainties were not included. Once the event structure of the top and background events will be better understood a "top likelihood" can be assigned to each event.

3.2. Dilepton Channel.

The top signature for these decay modes consists of a pair of high P_T leptons, missing E_T and jets. We selected events with isolated oppositely charged electrons or muons, with:

- P_T(lepton) > 15 GeV/c.

Electrons are detected inside the rapidity regions $|\eta| < 1.0$ and $1.26 < |\eta| < 2.2$ (plug calorimeter).

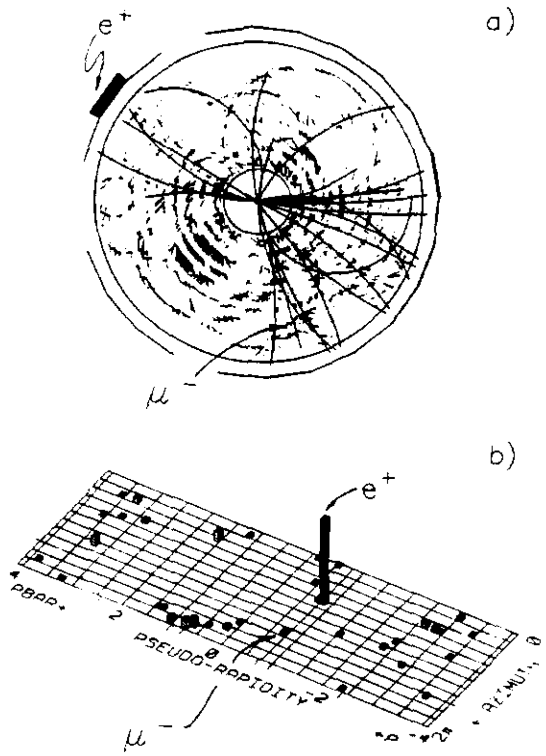

Figure 4: Displays of the top-quark candidate event:(a) view of the tracking chamber in the transverse plane and (b) calorimeter transverse energy in the $\eta - \phi$ space.

Although the central muon chambers only cover the region $|\eta| < 0.6$, we can extend our muon acceptance for this analysis to $|\eta| < 1.2$ by tagging muons as isolated, high P_T minimum ionising particles in the calorimeters.

For the ee and $\mu\mu$ final states we applied cuts to remove Z boson decays and off-Z-peak Drell–Yan events. No $\mu\mu$ or ee candidates are found, while one $e\mu$ candidate event survives all the cuts [7]. It has an electron of $E_T = 31.7$ GeV, a muon of $P_T = 42.5$ GeV/c, with $\Delta\phi = 137^o$, a jet of $E_T = 14$ GeV and an additional muon candidate in the forward detector with $P_T = 10$ GeV/c. Possible sources of background for this event include $Z \rightarrow \tau\tau$, WW and WZ production. Figure 4 shows a tracking chamber display and a calorimeter display for the candidate.

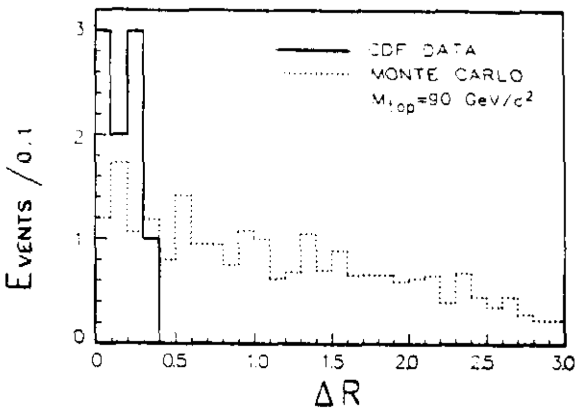

Figure 5: ΔR μ-jet

3.3.Tagging the b and extracting the limit

The current limit on the top quark was obtained combining the previous analyses with a new one, in which one attempts to tag the presence of b quarks through their semileptonic decay into a muon [9].

The sample which contained one high P_T lepton plus at least two jets was searched for the presence of an additional muon with $P_T < 15$ GeV/c. The low P_T muon candidate had also to be outside the cone of radius 0.5 (in $\eta - \phi$ space) centered on the two leading jets. In top decay leading jets would mostly be from the hadronic decay of W. The b quarks usually are not near these jets. This cut has the advantage of greatly reducing fake muon candidates for a top mass smaller than 100 GeV.

Figure 5 shows the distance between the low energy muon and the nearest of the two high Et jets. There are no events with $\Delta R > 0.5$ ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$).

We combine the result from the search in this channel with the result from the two high P_T leptons channel.

The 95 % confidence level upper limit on the cross section can be written as

$$\sigma_{t\bar{t}} < N_{top} / \int L dt \; \epsilon_{top}$$

where N_{top} is the 95% C.L. upper limit on the number of expected top events, $\int \mathcal{L}dt$ is the integrated luminosity and ϵ_{top} is the detection efficiency for observing top events.

The systematic uncertainties have to be considered. This is done by convoluting the Poisson probability distribution for N_{top} with the uncertainties in $\int \mathcal{L}dt$ and ϵ_{top}, which are assumed to be gaussian. With only one event observed, $N_{top} = 4.90$.

The cross-section limit can be translated into a lower limit on the mass of the top quark. Figure 6 shows the upper limits on $\sigma_{t\bar{t}}$ as a function of m_{top} together with the production cross section from ref.[4,5]. To set a lower limit on m_{top} we find the point at which the experimental curve crosses the lower (more conservative) bound of the theoretical prediction. We find that $m_{top} > 91 GeV/c^2$ at 95% C.L.

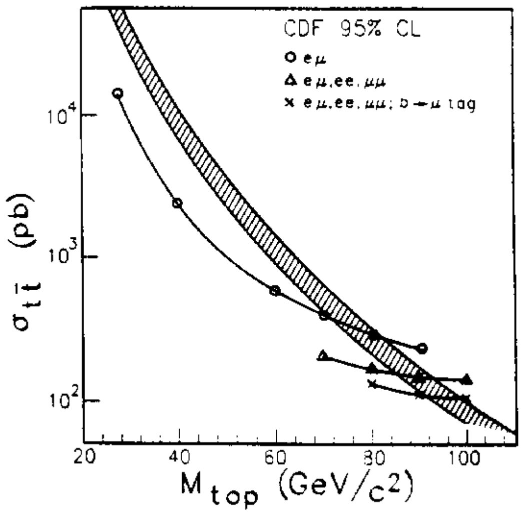

Figure 6: The CDF upper limit on the $t\bar{t}$ production cross section from the combined searches.

4. FUTURE PROSPECTS

Fermilab has an ambitious improvement program of the Tevatron which will upgrade its performances and extend its physics reach during the coming years.

Since the 1988–1989 run CDF has been improved both to handle the higher luminosity of the Tevatron and to enhance the physics capabilities of the experiment. The improvements include extended muon identification, improved low–P_T electron identification using a central preradiator, and a silicon vertex detector (SVX) that will allow the tagging of secondary vertices from the b quarks produced in top decays. Regardless of the decay channel used to detect events resulting from top production, the most convincing evidence that we do see top decay will be an enhanced rate of b quarks in the final state, above the rate expected from other sources. The SVX will be the primary detector by which b quarks will be tagged in $t\bar{t}$ events.

New analysis tools have been developed. For instance the study of the event topology will help to distinguish signal from background in both the single lepton and the dilepton channel.

It will be possible to use the τ signature for the top search. CDF already showed its capability to identify τ's [10]. The τ signal is very clean after requiring a narrow jet isolated in the central tracking chamber (CTC). During the last run the τ trigger was not very efficient, so that the analysis was limited by lack of statistics. With a trigger already in place at the beginning of this run, the τ analysis will become much more sensitive.

At this time of writing the 1992 collider run has begun. This run is expected to continue through early 1993 and provide approximately 25 pb^{-1}. A six month shutdown period will be followed by a second run with a projected integrated luminosity of 75 pb^{-1} [11].

Another experiment is currently running at the Tevatron: D0. This experiment, with its emphasis on calorimetry and muon identification, is competitive and also complementary to CDF, with its emphasis on central tracking and precision vertexing.

Our goals for the next future are the discovery of the top quark, a first measurement of its mass and the precise measurement of m_W. Assum-

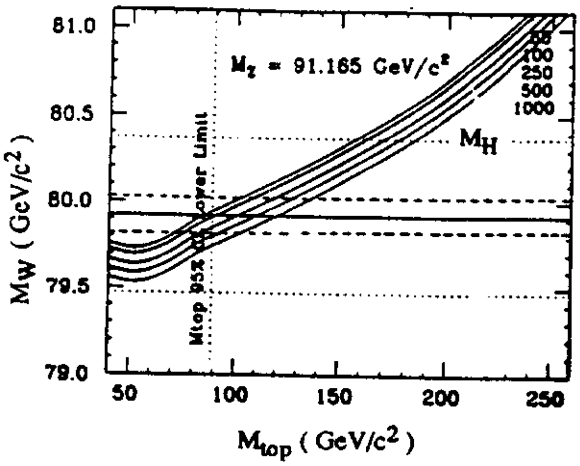

Figure 7: W mass vs. m_{top} is shown for different values of M_{Higgs}.

ing the Standard Model to be correct, the electroweak parameters (most notably the W mass) vary with m_{top} as a result of radiative corrections. It will be important to confirm that the top quark decays according to the minimal Standard Model.

The mass of the top is intimately connected to the mass of the Higgs. In Figure 7 we show the W mass (combined e and μ decay channels) as a function of the top quark mass, with the Higgs mass as a parameter. The dotted lines indicate the precision of the current CDF measurement of m_W and the limit on the top quark mass. The dashed lines indicate the window set by a 100 MeV/c^2 accurate measurement of m_W.

5. CONCLUSION

After several years of successful scientific work, CDF is getting into a really exciting period. It will be possible to make more stringent tests of the Standard Model, thanks to further improvements in the measurements of the mass and decay width of the W.

The top quark will either be discovered, or revisions in the Standard Model will be necessary.

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