Recent Results on Top Quark Physics at CDF

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Abstract

We present the latest results on the top quark obtained by the CDF experiment using a data sample of about 110 pb^{-1}. The data sample has been collected at the FermiLab Tevatron Collider with $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. We briefly describe the candidate event selection and then discuss the production cross section determination and the mass measurement. Combining the results from the channels with at least one W decaying leptonically into an electron or muon, we measure $\sigma_{t\bar{t}} = 7.5^{+1.9}_{-1.6}$ pb. Our best measured value for the top mass gives $M_t = 176.8 \pm 6.5$ GeV/c^2. We also report on the observation of $t\bar{t}$ production in the all hadronic decay channel using kinematic selection and b identification, and in the channel containing one hadronically decaying τ lepton. Finally we discuss the kinematics of top events and measure the matrix element $|V_{tb}|$ =1.12$\pm$0.12.

1 Introduction

At the Tevatron Collider top quarks are expected to be produced primarily in pairs, $p\bar{p} \rightarrow t\bar{t}$. In the framework of the Standard Model each top quark decays into a W and a b quark. The final state of a $t\bar{t}$ decay therefore has two W bosons and two b quarks.

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The $t\bar{t}$ decays can be characterized by the decays of the two W bosons. The *dilepton* category is represented by the case in which both W bosons decay leptonically, the *single lepton* by one W decaying leptonically and the other hadronically, and the *all hadronic* category by both W's decaying hadronically.

Direct evidence of the existence of the top quark was presented by CDF [1] in early 1994. Later, in 1995, both the CDF [2] Collaboration and the D0 [3] Collaboration announced conclusive discovery of the top quark. CDF has also identified top quark production events from other kinematic studies [4]. The CDF data presented here was collected during 4 years of data taking, from 1992 to 1995, and corresponds to a larger data sample of approximately 110 pb^{-1}. A characteristic signature of the top quark is the presence of jets initiated by b quarks. CDF uses b tagging information, especially secondary decay vertices in jets, as a powerful tool to identify the presence of b quarks in the candidate events.

In this paper we present the latest results on the top quark. We study new kinematic features of the events and compare them with the expected distributions from Monte Carlo. b–tagging information is used either as an event selection parameter, or to certify the top nature of kinematically top–like events.

2 The CDF Detector

A detailed description of the CDF detector can be found elsewhere [5]. Particle charge and momenta are measured in the central tracking chambers which reside in a 1.4 Tesla superconducting solenoid magnet. The tracking chambers provide a pseudorapidity coverage of $|\eta| <1.0$ [6]. Surrounding the tracking chambers, the electromagnetic and hadronic calorimeters are used in the identification and energy measurements of electrons, jets and photons. Muons are identified with drift chambers located outside the calorimeters. A three–level trigger is employed to select high transverse momentum (P_T) electrons and muons.

3 Dilepton Channel

In the standard dilepton channels (ee, $\mu\mu$ and $e\mu$) the event topology consists of two oppositely charged high P_T leptons, large missing transverse energy $\not\!\!E_T$ to account for the presence of two undetected neutrinos and two jets to account for the b quarks. The event selection requires two central and isolated leptons (e or μ only) oppositely charged, with $E_T^e \geq 20$ GeV or $p_T^\mu \geq 20$ GeV/c, large missing transverse energy ($\not\!\!E_T \geq 25$ GeV), and two central and energetic jets ($E_T \geq 10$ GeV). In order to suppress the background from Z production, we remove ee and $\mu\mu$ pairs with 75$\leq M_{ll} \leq$ 105 GeV/c^2. Additional background rejection is obtained by requiring that the $\not\!\!E_T$ vector should not be within 20 degrees of any jet or lepton in the transverse plane, for events with $\not\!\!E_T \leq$ 50 GeV. Nine events survive these cuts: 7 $e\mu$, 1$\mu\mu$ and 1 ee candidates (Fig. 1). The total background amounts to 2.1$\pm$0.4 events and is dominated by Drell–Yan production, $Z \rightarrow \tau\tau$ decays, fake leptons and WW events. We find that four of the nine dilepton candidate events contain at least one jet identified as a b jet. With a total acceptance for M_t =175 GeV/c^2 of (0.74$\pm$0.08)%, we measure the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ (DIL)=8.5$^{+4.2}_{-3.2}$ pb.

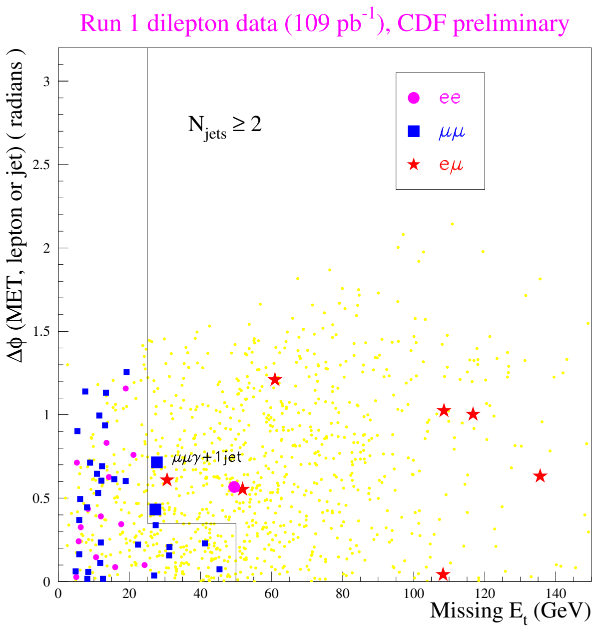

Figure 1: Azimuthal angle between $\not\!\!E_T$ and the nearest lepton or jet, versus the $\not\!\!E_T$ for standard dilepton events. The line represents the $\not\!\!E_T$ cut.

4 Single Lepton Channel

In the single lepton channel the event topology consists of a high P_T, isolated lepton (e or μ), $\not\!\!E_T$ from the neutrino and four or more jets from the hadronization of the quarks. For this analysis we require a single, high P_T lepton, large $\not\!\!E_T$ ($\not\!\!E_T \geq$ 20 GeV) and at least three energetic jets with $E_T \geq$ 15 GeV in the central region of the detector ($|\eta| \leq$2.0). The dominant background comes from direct production of W bosons in association with jets. This background can be reduced by requiring the presence of at least one b quark. We use two different techniques to identify b quarks. The first one is based on the search for displaced vertices from secondary b decays (SVX tagging). The efficiency of this method on $t\bar{t}$ events is 0.41$\pm$0.04. The second technique is based on the identification, inside a jet, of low P_T leptons from semileptonic b decays (Soft Lepton Tagging, or SLT). Its efficiency on $t\bar{t}$ events is 0.20$\pm$0.02.

Using the SVX method, we observe 42 b tagged jets in 34 events. The corresponding background amounts to 7.69$\pm$1.37 events. The total acceptance amounts to (3.52$\pm$0.65)% and we measure a top production cross section $\sigma_{t\bar{t}}$ (SVX)= $6.8^{+2.3}_{-1.8}$ pb. The SLT method identifies 44 tagged jets in 40 events, with a background of 24.6$\pm$3.0 events. The total acceptance of the SLT tagging method is (1.73$\pm$0.28)% . We measure a production cross section $\sigma_{t\bar{t}}$ (SLT)=$8.0^{+4.4}_{-3.6}$ pb. The main contribution to the background comes, in both methods, from $Wb\bar{b}$, $Wc\bar{c}$, $b\bar{b}$ events and fake tags. In Fig. 2 we show the observed tags for the SVX tagging method as a function of the jet multiplicity of the events, compared to the expectations from the background plus $t\bar{t}$ production. In Fig. 3 the same distribution is shown for the SLT tagging method.

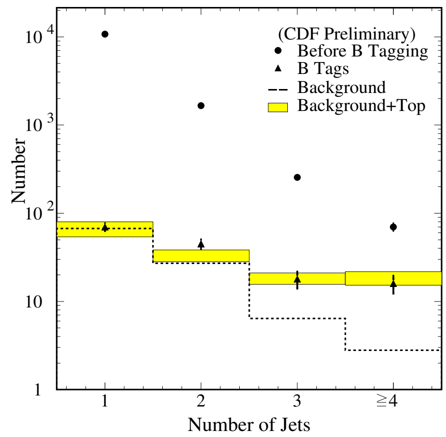

Figure 2: Jet multiplicity distribution of SVX tagged jets in the lepton plus jets channel.

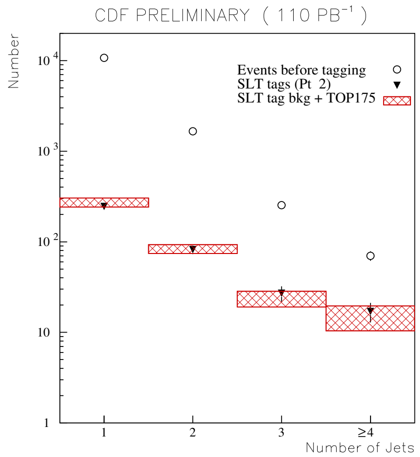

Figure 3: Jet multiplicity distribution of SLT tagged jets in the lepton plus jets channel.

5 All Hadronic Channel

The all hadronic final state represents a large fraction ($\approx$44%) of all the $t\bar{t}$ decay channels. This decay channel presents a topology with 6 jets in the final state: 4 jets are due to the 2 W's and the 2 jets come from the b quarks. The final $t\bar{t}$ state is characterized by central jets with large transverse energy. The signal/background (S/B) ratio is very small at the trigger level since the QCD multijet background is overwhelming. To achieve a significant improvement in S/B ratio, the strategy of the analysis consists in combining both a kinematic and a b tagging selection.

A multijet dedicated trigger selects 230,000 events with at least four jets with $E_T \geq 15$ GeV. At this level the S/B is about 1/1000. After we apply a tight kinematical selection we manage to strongly reduce the background while mantaining a reasonable efficiency for the signal. We begin by requiring high jet multiplicity ($\geq$ 5 jets with $E_T \geq$15 GeV and $|\eta| \leq$2) and large total transverse energy, $\Sigma E_T \geq$300 GeV, "centrally" deposited in the detector ($\Sigma E_T/\sqrt{\hat{s}} \geq$0.75). Additional separation between top and background events is obtained by a cut on the "aplanarity–ΣE_T" space ($A + 0.0025 \times \Sigma_3^N E_T \geq 0.54$). In addition to the kinematical selection, we also require at least one SVX b tagged jet (with $E_T >$25 GeV) in our final selected sample. The sample has a ratio S/B$\approx$ 1/20, which becomes S/B$\approx$ 1/2, after b tagging is required. We observe 230 b tagged jets, with a background of 160.5$\pm$10.4 from QCD heavy flavor production and mistags. Fig. 4 shows the number of tags as a function of jet multiplicity, compared to the expected background. There is an excess of tagged jets in the jet multiplicity bins N=5,6 and $\geq$7. The probability that such a number of tags observed is purely due to a background fluctuation is $1.5 \times 10^{-4}(3.6\sigma)$. The number of events with at least one SVX b tag is 192 with a corresponding background of 137.2$\pm$11.3 events.

The acceptance for the kinematical requirements for m_{top}=175 GeV/c^2 amounts to $(9.9^{+3.0}_{-3.5})$%. We measure the production cross section to be $\sigma_{t\bar{t}}$ (HAD)=$9.6^{+4.4}_{-3.6}$pb.

6 Tau plus Lepton Channel

We also present a new search for $t\bar{t}$ dilepton events with one electron or muon and one additional hadronically decaying tau lepton [7]. In this case one lepton (e or μ) is selected as in the dilepton case described earlier, while the other one is required to be identified as a τ with hadronic decay. Hadronic tau decays are identified using tracking and calorimeter quantities.

We use kinematical variables to isolate $t\bar{t}$ events by requiring:

- $N_{jets} \geq$2, where N_{jets} is the number of jets at $|\eta| <$2.0 and $E_T >$ 10 GeV;
- $H >$180 GeV;
- $\sigma_{\not{E}_T}$>3 (GeV)$^{1/2}$, where $\sigma_{\not{E}_T}$is the significance of the missing transverse energy $\not{E}_T$.

The branching ratio for $e\tau$ and $\mu\tau$ events is 4/81, i.e. the number of dilepton events could be doubled including tau decays in the dilepton analysis. However, the B.R. for hadronic

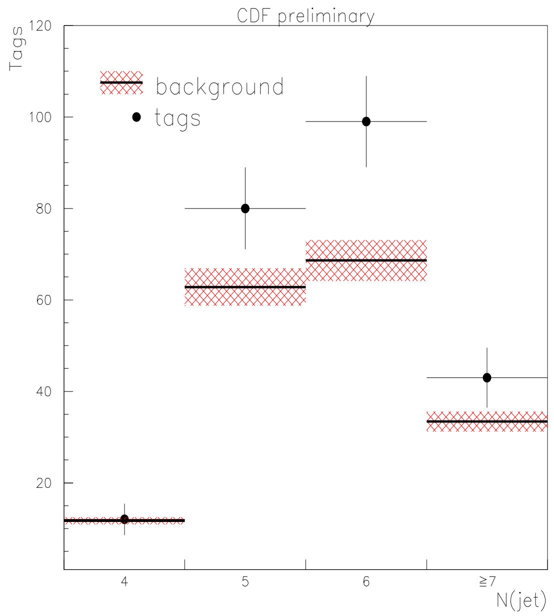

Figure 4: Jet multiplicity distribution of the tagged jets in the all hadronic channel.

τ decays is about 64% and each τ decay involves an undetectable neutrino, which decreases the kinematic acceptance for the τ decay products. The τ identification is not as efficient as for e and μ, if we want to keep under control the background from jets. The total acceptance for τ's is therefore smaller than for standard dileptons.

We look for high–P_T isolated tracks (P_T >15 GeV/c). To perform the τ identification we use primarily the tracking isolation (I_{trk} <1 GeV/c) in a cone ΔR=0.4 as a powerful way to discriminate beween signal and background. Furthermore, using calorimeter information, we discriminate taus from electrons and muons by rejecting highly electromagnetic calorimeter clusters and minimum ionizing particles, respectively. Within these selection criteria the τ–id efficiency is 59±4%. We call this method a "track–based" τ algorithm. The total acceptance is (0.088±0.010)% for M_{top}=175 GeV/c^2. In 110 pb^{-1} of data we expect approximately 1 signal event. We observe 4 candidate events, 2 $e\tau$ and 2 $\mu\tau$ events, with a total background of 0.89±0.22 events.

Decays of τ leptons often produce neutral pions. We can thus use calorimeter informations to identify π°'s. We can add to the previous selection a search for the photons from the decay $\pi^\circ \to \gamma\gamma$ in the electromagnetic shower detector. Using this method we can also extend the search to three–prongs decays of τ leptons. The τ –id efficiency becomes 51±3%. We call this method a "calorimeter–based" τ algorithm. The total acceptance of this selection is (0.119±0.014)% for M_{top}=175 GeV/c^2. The expected background is

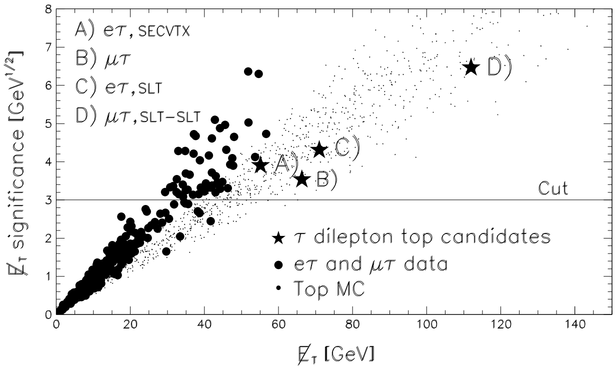

Figure 5: The distribution of $\sigma_{\not{E}_T}$vs $\not{E}_T$ for tau dileptons in CDF data (110 pb^{-1}). Two candidate events have soft lepton b tags (SLT); one event is b tagged with the secondary vertex algorithm (SECVTX).

1.96$\pm$0.35 events. Although this search includes one and three–prongs τ decays, we do not find any additional event. We observe the same 4 candidate events as in the track–based method. Fig. 5 shows $\sigma_{\not{E}_T}$versus $\not{E}_T$ for all tau dilepton events.

Using the calorimeter (track) based τ algorithm, a first measurement of the $t\bar{t}$ cross section based on these events yields $\sigma_{t\bar{t}} = 15.6^{+18.7}_{-13.2}(32.1^{+25.4}_{-17.7})$ pb. The uncertainties are statistical only. Studies of the systematic errors are in progress.
We apply the soft–lepton (SLT) and secondary–vertex (SVX) tagging algorithms [2] for identifying jets from b quarks. Three of the four candidate events are b tagged. For top signal plus background we expect $0.64 \pm 0.12(stat)$ events tagged by SVX and observe one event. In the SLT case we expect $0.37 \pm 0.06(stat)$ tagged events and observe two. The probability to observe 2 or more events when 0.37 events are expected is 6%. One event has an SLT–SLT double b tag. We estimate the mean expected total background with b tagging to be (0.23$\pm$0.01) events. The probability for the background to fluctuate to the 3 observed events is 0.13% (3 σ).

7 Production Cross Section

The $t\bar{t}$ cross section has been calculated in each of the samples described above. We obtain a better statistical result by combining the *standard dilepton* and the *single lepton* channels, and taking into account the correlations. Work is in progress to include in the measurement also the all hadronic sample, which is correlated both in acceptance and tagging efficiency with the SVX sample. Assuming $M_t = 175$ GeV/c^2, as measured by CDF, we obtain $\sigma_{t\bar{t}} = 7.5^{+1.9}_{-1.6}$ pb. In Fig. 6 we show the CDF measurement for the top cross section as a function of the top mass, compared with some of the most recent theoretical calculations [8] [9] [10].

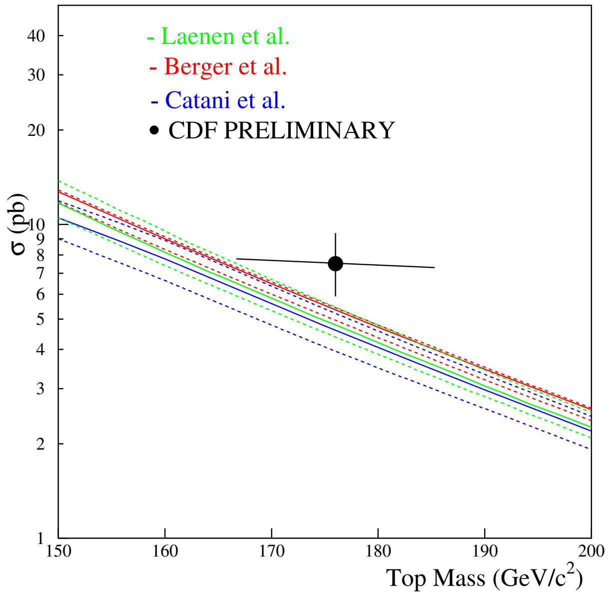

Figure 6: Combined $t\bar{t}$ cross section versus M_t (point) compared to theory (bands).

8 Mass Measurement

We obtain the best measurement of the top mass from the lepton plus jets channel. We select the sample by requiring the presence of a fourth jet in the events. A total of 153 events is found. If we require one of the four highest E_T jets to be tagged, we are left with 34 events and a background expectation of $6.4^{+2.0}_{-1.5}$ events. We fit the lepton plus jets events to the $t\bar{t}$ hypothesis, using a constrained kinematic fitting method [1]. The tagged jet is required to be one of the b jets. Both possible solutions for the (unmeasured) longitudinal component of the neutrino momentum are sought. Out of 12 possible combinations we choose the solution which has the lowest χ^2 ($\chi^2 <$10).
In addition to our previous method [1] we make optimal use of the b tagging information contained in our data sample. Monte Carlo studies indicate a reduced error if the tagged events are subdivided into different tagging categories and a subset of the non–tagged events (events with all four leading jets with $E_T >$15 GeV) is added.
The reconstructed mass distribution is shown in Fig. 7, together with the expected back-

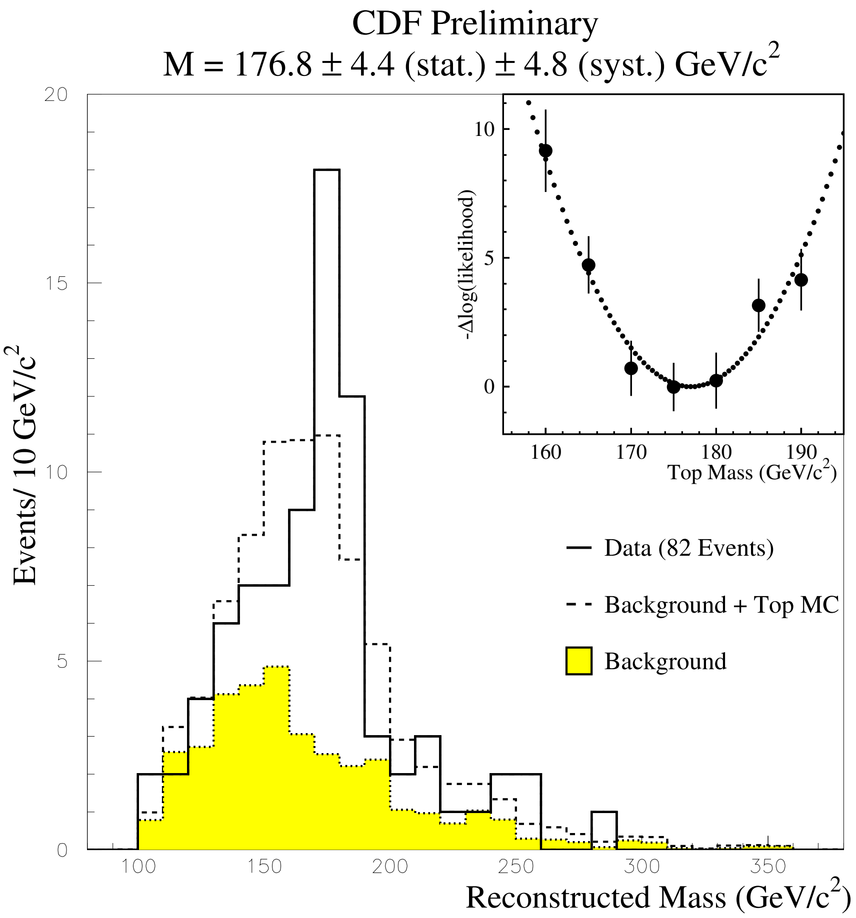

Figure 7: Top mass distribution in the lepton plus jets sample for events with at least one b tagged jet.

ground and a combination of top Monte Carlo and background. The likelihood fit is shown in the insert. The curve has a minimum at 176.8 GeV/c^2 and the statistical uncertainty is 4.4 GeV/c^2. The main systematical uncertainties come from the jet energy measurement and propagate to the top mass through the fit. The final top mass measurement using this method gives: M_t = 176.8$\pm$4.4(stat)$\pm$4.8(syst) GeV/c^2.
As an additional check in these events, the hadronic W decays are reconstructed. An even stronger proof that b tagged events are due to top quark pairs requires the identification of both W bosons in the events. We can reconstruct the hadronically decaying W using $W+\geq 4$ jets events when two jets are b tagged. The two non–tagged jets should be the W decay products. Ten events are in our final sample. In the upper plot of Figure 8 we show the invariant mass spectrum of the two untagged jets. In the middle and lower plots we show the dijet invariant mass when using only one b tagged jet and the two tagged jets, respectively. A peak in the dijet mass spectrum around 80 GeV can be observed in the untagged jet sample. Assuming a flat distribution, as for b tagged dijet events, the probability to obtain such a peak by statistical fluctuation is approximately 3.5 σ.

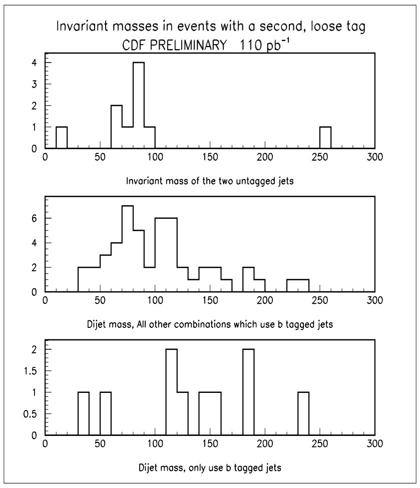

Figure 8: Dijet mass distributions for the $W+\geq 4$ jets events: for the two untagged jets (upper plot), using only one b tagged jet (middle plot), for the two b tagged jets (lower plot).

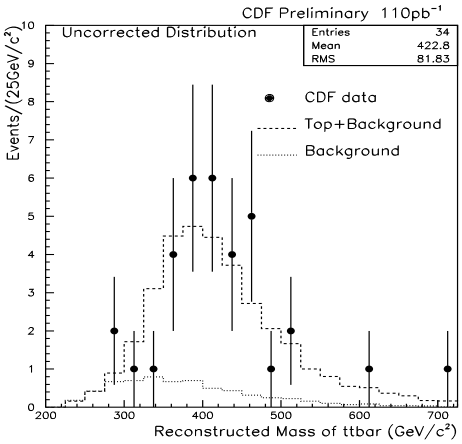

Figure 9: Distribution of M($t\bar{t}$) for the b tagged mass sample.

CDF has also measured the top mass in the all hadronic and in the standard dilepton channels. In the all hadronic channel the mass distribution is obtained with a constrained fit similar to that used for the lepton plus jets sample. The final results yields $M_t = 187 \pm$

$8(stat) \pm 12(syst)$ GeV/c^2. In the dilepton channel we use a different technique because of the presence of a second neutrino makes the kinematic constrained fit impossible. We use instead the energy distribution of the two highest E_T jets in the events, which is sensitive to the top mass. The result is M_t $=159^{+24}_{-22}(stat) \pm 17(syst)$ GeV/c^2. These results are consistent, within their errors, to the value obtained from the lepton plus jets channel. Work is in progress to combine these results together.

9 Kinematic Properties of the $t\bar{t}$ system

The sample used for the measurement of the top mass is a portion of the lepton plus jets data set with the additional requirement of at least four jets, with the E_T threshold on the fourth jet lowered to 8 GeV. Kinematical properties of the $t\bar{t}$ system (other than the top mass) are compared with the expectation from the Standard Model. We define two samples: one before b tags (153 events), and another for events with at least one SVX or SLT tag (34 events). The background in the first sample amounts to 98 ± 11 events, while in the tagged sample it amounts to $6.4^{+2.1}_{-1.4}$ events. Each event is kinematically constrained to the $t\bar{t}$ hypothesis assuming the tagged jet to be one of the b partons. From the fit we extract several kinematical quantities of the $t\bar{t}$ system but, for the time being, we work with *observed* variables, biased by detector resolution, selection cuts and the fitting algorithm, instead of the *true* ones. These quantities are then compared with those expected from Monte Carlo events ($t\bar{t}$ plus background). This is not only an important check of the consistency of the $t\bar{t}$ production properties with the Standard Model, but can also evidentiate effects of non standard $t\bar{t}$ pair production. As an example of this consistency check we show in Fig. 9 the distribution in the tagged sample of the invariant mass of the $t\bar{t}$ system. No discrepancy with respect to the Standard Model predictions is observed in this and in all the other variables studied.

10 Decay Properties: measurement of $|V_{tb}|$

The fraction $B = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 \ |V_{ts}|^2 \ |V_{tb}|^2}$ of top decaying to bottom has been determined from the ratio of b tagged and untagged events. Two samples have been used: a W+jet sample (68 events, 10 with one b tag, 5 with two b tags), in which the top content has been enhanced by cuts on kinematical variables (similar to those in Ref. [4]), and the standard dilepton sample, much cleaner. The two samples are orthogonal and the results are combined in a single measurement of B.

From the number of untagged, single and double tagged events, background estimates, acceptances and tagging efficiency, we derive a likelihood function in which B is a free parameter. The maximum of this function is obtained for $B = 1.23^{+0.37}_{-0.31}$, where the uncertainty quoted is mainly statistical. Under the assumption of three generation unitarity, we derive the value of the Cabibbo–Kobayashi–Maskawa matrix element $|V_{tb}| = \sqrt{B} = 1.12 \pm 0.12$, or $|V_{tb}| > 0.78$ (95% C.L.). If we remove the unitarity constraint and use the available estimates for $|V_{td}|$ and $|V_{ts}|$, we obtain the limit $|V_{tb}| > 0.05$ (95% C.L.).

11 Conclusions

We have reported the results obtained in 110 pb^{-1} of data collected with the CDF detector, consider several decay channels. We have measured the top production cross section using the dilepton and single lepton channels to be $\sigma_{t\bar{t}}$ (DIL,SVX,SLT)=$7.5^{+1.9}_{-1.6}$ pb. We also measured the top mass value. Our best result comes from the single lepton channel, and it yields $M_t = 176.8 \pm 6.5$ GeV/c^2. Furthermore, evidence for $t\bar{t}$ production in the all hadronic channel has been presented, with a measured cross section in agreement with $\sigma_{t\bar{t}}$ (DIL,SVX,SLT). We have also presented the results for $t\bar{t}$ production in the τ plus lepton channel. For a deeper understanding of top properties we have compared some kinematic distributions of the $t\bar{t}$ system with the Monte Carlo predictions. The results are still preliminary, but a good consistency is seen between the data and the Monte Carlo. Finally, we have made a preliminary measurement of the Cabibbo–Kobayashi–Maskawa matrix element $|V_{tb}| = \sqrt{B} = 1.12 \pm 0.12$.
Fig. 10 shows the world average results on the top mass combined with the W mass measurements. This information, although statistically limited, can be used to set some constraints on the mass of the neutral Higgs boson.

12 Acknowledgements

I would like to thank the organizers of this conference, our russian hosts for the friendly and gracious reception, and my fellow collaborators for the pleasure in representing them and their work. I also wish to thank all the people who made this conference a special place.

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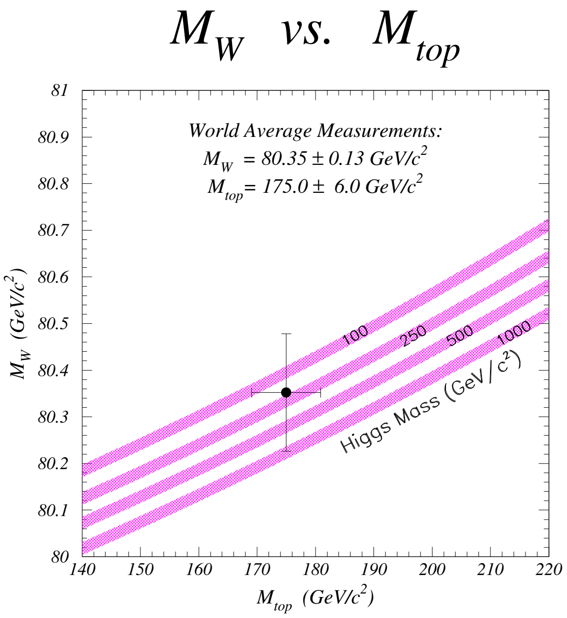

Figure 10: World average results of M_W versus M_t , compared to Standard Model predictions for various H° masses.

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