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Top Decays and Mass with CDF

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TOP DECAYS AND MASS WITH CDF

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Abstract

We report preliminary results on top quark decays and measurements of the top mass recently obtained by the CDF collaboration, using a data sample of about 110 pb^{-1} collected at the Tevatron collider. Upper limits for non Standard Model top decays into W + q (non b quark), Z + q and γ + q are given. Top mass measurements are obtained in three topologies for $t\bar{t}$ production and decay into W b: lepton + $\geq$ 4 jets, di-lepton and all hadronic final states. The most precise measurement is obtained in the lepton + $\geq$ 4 jets topology using 34 events which have at least one jet tagged by the SVX or SLT b-tagging algorithms and a good constrained kinematics fit. Mass analyses in the three channels yield:

$M = 175.6 \pm 5.7$ (stat) $\pm$ 7.1 (syst) $\mathrm{GeV/c^2}$	lepton + jets ($\geq$ 1 b-tags)
$M = 159\ ^{+24}_{-22}$ (stat) $\pm$ 17 (syst) $\mathrm{GeV/c^2}$	di-lepton + jets
$M = 187 \pm 8$ (stat) $\pm$ 12 (syst) $\mathrm{GeV/c^2}$	multijet ($\geq$ 1 b-tags)

1 Introduction

First evidence of $t\bar{t}$ production at the Tevatron (1.8 TeV $p\bar{p}$ collider) was reported by CDF in April 1994 [1]. That report was confirmed in early 1995 by both CDF [2] and D0 [3], when both experiments announced a definite discovery of the top quark. By now a number of candidate events for detailed cross section, decay properties and mass measurement are available in both experiments. In this report we discuss recent CDF results on limits of top decays in non Standard Model (SM) channels and recent more precise top mass measurements.

The event samples used in these analyses corresponds to about 110 pb^{-1} of data. The top quark is expected to decay into W b with the W decaying into lepton pairs or quark pairs. We report here only on $t\bar{t}$ topologies with a.) one W decaying into a lepton (e or μ + jets, 30% of the final states), b.) both W's decaying into leptons (e or μ +jets, 5% of total), c.) both W's decaying into jets (multijets, 44% of total). The analyses reported here use two techniques for tagging b jets: reconstruction of displaced vertices by using a silicon vertex detector (SVX algorithm), or detection of a non-isolated lepton, e or μ, associated with a b or c jet (SLT algorithm).

2 Search for Non-Standard Top Decays

Search for t → W + q' (u,d,s,c) The SM predicts that the top quark decays mostly into W + b. The CKM matrix element $|V_{tb}|$ is constrained by the SM to be: $0.9989 < |V_{tb}| < 0.9993$. This leaves very little room for decays into quarks other then b. With the available data we measure R_b, the ratio of $(t \rightarrow W\ b)/(t \rightarrow W\ q)$.

This analysis was done using two different sets of data: 1.) the di-lepton and the lepton +jets($\geq$ 1 b-tagged jet) samples and 2.) the di-lepton (7 events) and the W+jets samples with kinematic cuts to enhance the top content (214 events). We use a simple model to reproduce the observed number of events with 0, 1 and 2 b-tagged jets. In each case we combine all the data in a likelihood fit with R_b as a parameter. The results of the first analysis have been previously reported [4] and agree with those reported here. From the second analysis we obtain:

$$R_b = BR(t \rightarrow W+b)/BR(t \rightarrow W+q) = 1.23\ ^{+0.37}_{-0.31} \quad \text{or} \quad R_b > 0.61 \quad (95\%\ CL)$$

We can use the measured value of R_b to measure $|V_{tb}|$. Using the CKM matrix and assuming unitarity we obtain

$$|V_{tb}| = 1.12 \pm 0.16\ (\text{stat + syst}) \quad \text{i.e.} \quad |V_{tb}| > 0.78 \quad (95\%\ \ CL)$$

Relaxing the unitarity constraint and using $0.004 < |V_{td}| < 0.014$, $0.034 < |V_{ts}| < 0.046$, we obtain $|V_{tb}| > 0.050$ (95% CL). Work on combining the two results is in progress.

Search for t → Z q. This is a flavor changing neutral current (FCNC) decay, and can be calculated in the SM with FCNC to be BR(t → Z q) $\leq$ 0.001 [5]. We search in the channels $p\bar{p} \rightarrow t\bar{t} \rightarrow ZqZ\bar{q} \rightarrow \ell^+\ell^-$ + 4 jets requiring lepton(e or μ) $P_T > 20$ GeV and jet $E_T > 20$ GeV. Background (from ZZ +jets and Z +jets) is expected to be B = 0.60 ± 0.14(stat) ± 0.12(syst) events. We find one Z → $\mu\mu$ event. Assuming that it is signal, we set a limit:

$$BR(t \rightarrow Z\ q) < 0.44 \quad (90\%\ CL)$$

Search for t $\rightarrow \gamma$ q . Here q is u or c quark. These are also FCNC decays and are expected to be in the range of $10^{-7} - 10^{-12}$. For the b quark CLEO finds $b \rightarrow s\gamma \sim 2 \times 10^{-4}$. We use the channel $q\bar{q} \rightarrow t\bar{t} \rightarrow$ W b γ q. To reduce the background we require two signature for this final state. We use two topologies: a.) W $\rightarrow \ell\nu$, i.e., we search for $\gamma + \ell + \not{E}_{\rm T} + \geq 2$ jets events, b.) W $\rightarrow q\bar{q}\prime$, i.e., we search for $\gamma + \geq 4$ jets and a b-tag. After some kinematical cuts the background is expected to be 0.06 events. One event of type a.) is observed. Assuming it is signal we can set a limit:

$$\mathrm{Br}(t \rightarrow \gamma\ q) < 0.029 \qquad \text{(at 90\% CL)}$$

3 Measurement of the Top Mass

Top quarks are produced in pairs in a $p\bar{p}$ collider. As discussed in the introduction we have analysed the di-lepton (either e or μ) plus ≥ 2 jets, the lepton plus ≥ 4 jets, and the multijets final states. Events with decay W $\rightarrow \tau$ are mostly rejected by our event selection. Special criteria are used to select the τ's [6], but these events are not used in the mass analysis.

3.1 Lepton plus jets final state

We fit the lepton + jets events to the $t\bar{t}$ hypothesis, using a constrained kinematic fitting method as described in Ref [1]. The following chain of subprocesses is kinematically constrained:

vertex	process
1	$p\bar{p} \rightarrow t_1 + t_2 + X$
2	$t_1 \rightarrow b_1 + W_1$
3	$t_2 \rightarrow b_2 + W_2$
4	$W_1 \rightarrow \ell + \nu$
5	$W_2 \rightarrow j_1 + j_2$

In addition we require $M_{t_1} = M_{t_2}$. We constrain the W to $M_W = 80.2$ GeV and $\Gamma_W = 2.1$ GeV. There are 20 equations, 18 unknowns, which implies a two constraint fit. Additional criteria are as follows: a.) to reduce combinatorics, the 4 highest E_T jets in the event are used b.) both possible solutions for the P_z^ν are tried c.) if there are b-tagged jets, they are required to be the b jets in the fit. d.) out of the 24 (12 for one b-tag, 4 for two b-tags) possible combinations, the solution with the lowest χ^2 is chosen ($\chi^2 < 10$).

The sample used here is the same one used for cross section measurement [1, 2, 6], i.e., we use the lepton + ≥ 3 jets sample ($E_T > 15$ GeV and $|\eta| < 2.0$ for the 3 jets), with an additional jet with $E_T > 8$ GeV and $|\eta| < 2.4$. For the top analysis jets are obtained by the cone algorithm with cone radius of 0.4. The major sources of background to the top signal are: (a) non-W events, (b) mistagged jets and (c) W$b\bar{b}$ and W$c\bar{c}$ events. The first two backgrounds are calculated from the data, the others from Monte Carlo using the measured b-tagging efficiency. A total of 153 events with at least four jets are found (calculated background $N_{nt} = 98 \pm 9$ events), 37 of which have at least one b-tagged jet (calculated background of $6.4^{+2.0}_{-1.5}$ events).

The distribution of the reconstructed mass for the sample with no b-tagging requirement is shown in Figure 1a. Out of the 37 events with at least one b-tag there are 34 fully reconstructed events ($\chi^2 < 10$). The mass plot is shown in Figure 1b. The mass distributions for the two b-tagging algorithms are quite consistent with each other. There are 20 events with an SVX tag(efficiency 41%) and 21 events with an SLT (efficiency 31%, but larger background than the SVX). Some jets have tags from both algorithms.

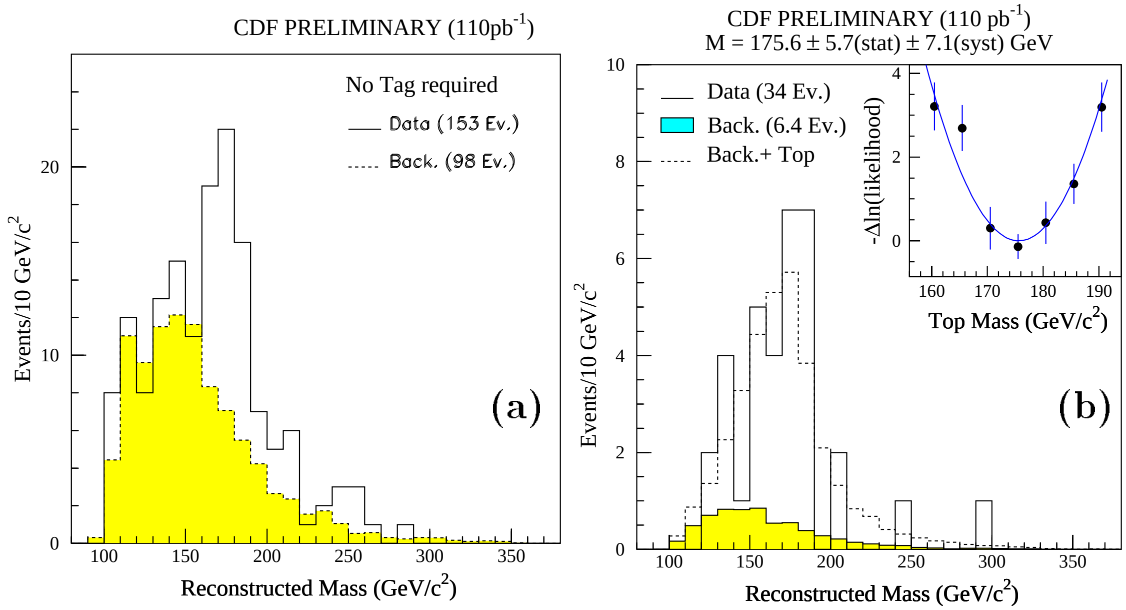

Figure 1: Top mass distribution for events with a lepton and at least four jets. (a) No tag requirement on the jets is made. (b) Only events with at least a tagged jet are shown.

The curves in Figure 1 use a.) the HERWIG Monte Carlo at 175 GeV for top and b.) the VECBOS+HERWIG Monte Carlo for the background. We use a likelihood method to determine the top mass and the background [1]. The background is constrained (with error) to $6.4^{+2.0}_{-1.5}$. The fit gives 6.3 ± 1.7 events and:

$$M_{top} = 175.6 \pm 5.7 \text{ (stat) GeV}$$

The statistical error on the top mass is obtained from the likelihood fit shown in the insert of Figure 1b. We have checked by Monte Carlo that the value of $\delta M = 5.7$ GeV is compatible with expectation. A set of 1000 pseudo-experiments of 34 events each with a background of 6.4 events is performed. The value 5.7 GeV is not far from the peak of the distribution of errors.

3.2 Systematic Uncertainties on Top Mass

The systematic errors on the top mass have been discussed in details in Ref [1]. A better understanding of the different contributions has been gained since then, and a lot of studies have been made to reduce some of the uncertainties that contribute the most.

The largest uncertainty comes from the uncertainty in the jet energy measurement, which we divide in many parts:

- Energy scale uncertainty (cone of 0.4). The systematic error on the relative and absolute corrections amounts to 4.1% at 8 GeV to 3.7% at 200 GeV of the uncorrected jet E_T.

- Soft Gluon radiation (error on E_T for $\Delta R > 0.4$). This uncertainty amounts to 5.6% at 8 GeV to 1.4% at 150 GeV uncorrected jet E_T.
- Hard gluon radiation,i.e., effects of gluon radiation that generates extra jets (see below).

We correct each jet using the CDF standard corrections [1] and then we apply top specific corrections to go from jet to parton energy. A major ingredient for the evaluation of uncertainties as well as for the likelihood method employed to obtain a mass value, is the use of Monte Carlo events. We need to check that Monte Carlo and data agree in describing the jets.

Table 1 shows the different sources of systematics. Due to space limitation we only discuss here some of the recent studies and refer to earlier publications for the rest [1, 2]. New studies have been made on energy scale uncertainties [7] and on soft gluon radiation effects. For the latter we study the jet shape, i.e., the energy flow in the cone centered around the jet direction, which is determined by QCD parton shower and by fragmentation. The difference between the data and the Monte Carlo provides the systematic uncertainty on the top mass from this source. We have used W+jets , Z+jets and $b\bar{b}$ events. The results of data and Monte Carlo comparison for W+jets events are shown in Figure 2. From this we have derived the jet uncertainty quoted above. (Note that for M(top) = 175 GeV, the average jet is fairly energetic: 55 GeV for jet from W and 67 GeV for b jets). Hard gluon radiation effects have been estimated by varying in the HERWIG Monte Carlo the percentage of events for which the jet from top decay (at the generator level) is considerably displaced from the one used in the mass fit. We obtain the uncertainty shown in the table.

Systematics	Value	
	GeV	(%)
Jet E_T Scale	3.1	1.8
Soft Gluon Effects	1.9	1.1
Different Generators	0.9	0.6
Hard Gluon Effects	3.6	2.1
Fit Configuration	2.5	1.4
b-tagging Bias	2.3	1.3
Background Spectrum	1.6	0.9
Likelihood method	2.0	1.1
Monte Carlo statistics	2.3	1.3
Total	7.1	4.0

Table 1: Systematic uncertainties on the top mass.

To check the jet energy calibration and systematic uncertainty on the energy scale we use Z+jets balancing. The Z mass and P_T are measured via the lepton pair decay modes whereas the jets recoiling against the Z's use the calorimeters and are subject to the systematic errors discussed above. Figure 2 shows the Z-jet balancing for both the data and Monte Carlo. This check is complicated by the so called "K_T kick", i.e., the Z and the jets have an intrinsic unbalance due to the initial P_T of the system ($\sim$ 5 GeV from HERWIG).

To evaluate the error on the mass from each of the jet uncertainties we use Monte Carlo, i.e., we perform a set of pseudo-experiments with all jets shifted by one σ uncertainty. We apply the kinematic fitting and the likelihood procedure to obtain a new mass. The shift of the new mass gives the desired uncertainty, as shown in Table 1. The final result is:

$$M_{top} = 175.6 \pm 5.7 \text{ (stat)} \pm 7.1 \text{ (syst)} \text{ GeV}$$

3.3 All Hadronic and Di-lepton Final States

CDF has also measured the mass in events where both W's decay into quark pairs or both decay into a lepton. Details about the data samples for these two analyses can be found in the

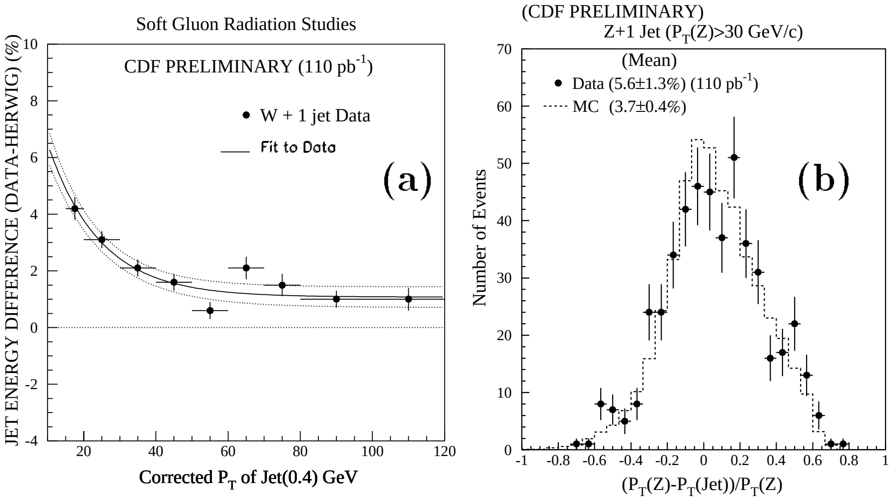

Figure 2: Top mass systematics studies: (a) data and Monte Carlo comparison of out-of-cone energy and (b) Z+jet balance .

talk by P. Azzi at this Conference [6].

All Hadronic Decay modes. Briefly, these events were obtained from the multijet triggers. For the mass analysis at least 6 jets are required (E_T > 15 GeV, $|\eta| < 2.0$, Δ $R_{min} \geq 0.5$). There is also an aplanarity requirement and that the total transverse energy be $\sum E_T \geq$ 200 GeV. Finally, we require at least one jet tagged by the SVX. A total of 142 events pass all requirements. The background, evaluated from the data [6] is calculated to be 109 ± 7 events. Figure 3a shows the invariant mass distribution obtained with a constrained fit similar to that used for the lepton + jets sample. The systematic errors are also evaluated as for the lepton + jets case. The final result is:

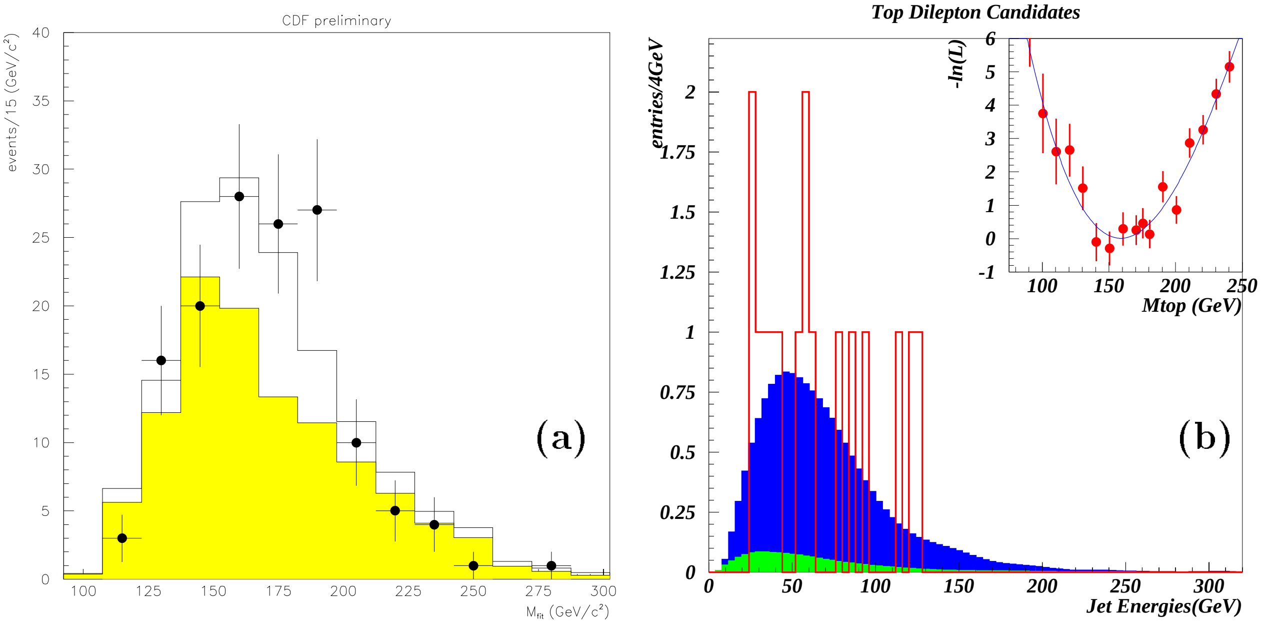

Figure 3: (a) Top invariant mass in hadronic channel and (b) Jet E in di-lepton channel.

$$M = 187 \pm 8(\mathrm{stat}) \pm 12(\mathrm{syst}) \ \ \mathrm{GeV}$$

Di-lepton Channel. This analysis uses the same data sample as the lepton plus jet analysis with the additional requirement of a second lepton [6]. Here we use an additional cut, $H_T >$ 170 GeV to reduce background. After this cut we have 8 events with a background of 1.1 ± 0.3 events.

The presence of a second neutrino makes the simple kinematic constrained fit impossible (three additional missing quantities), so we use a kinematic variable sensitive to the top mass: the b jet energy turned out to be the best variable. Figure 3b shows the distribution of the jet E_{jet} for the 8 events and the expectation from Monte Carlo. A likelihood fit finds a mass value of:

$$M = 159^{+24}_{-22}(\mathrm{stat}) \pm 17(\mathrm{syst}) \ \mathrm{GeV}$$

4 Summary of Results

We have reported studies of top decays and new results on the top mass measurement. Using the CDF W mass measurement and our best top mass value, we can check consistency with expectations from the SM.

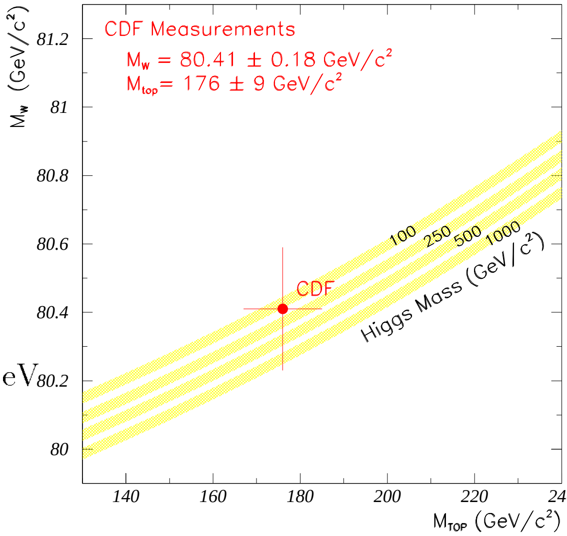

Figure 4 shows the relationship of the W and top mass for different ranges of the Higgs mass.

Results on top decays are as follows:

$R_b = (t \to W{+}b)/(t \to W{+}q) > 0.61$ 95% CL
$BR(t \to Z\,q) < 0.44$ (90% CL)
$Br(t \to \gamma\,q) < 0.029$ (90% CL)

We have measured the top mass in several channels:

Lep.+jets: $M = 175.6 \pm 5.7(\mathrm{stat}) \pm 7.1(\mathrm{syst})$ GeV
Multijet: $M = 187 \pm 8(\mathrm{stat}) \pm 12(\mathrm{syst})$ GeV
Di-Lept.: $M = 159^{+24}_{-22}(\mathrm{stat}) \pm 17(\mathrm{syst})$ GeV

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