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CDF Results on Top

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CDF has established the existence of the top quark. Results from $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV are presented. In the dilepton final state we find seven events with a background of 1.3 ± 0.3. In the e, μ + ν + jets channel with a b identified via a secondary vertex detector (SVX), we find twenty one events with a background of 5.5 ± 1.8. We measure the top quark mass to be 176 ± 8 (stat) ± 10 (syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $7.6^{+2.4}_{-2.0}$pb. The integrated luminosity for the results presented in this talk is 67 pb^{-1}. The CDF detector needs to be upgraded for our next run. The integrated luminosity for the next run is expected to be more than 1000 pb^{-1}.

1 Introduction

This talk is about the CDF observation of top.[1] The topics covered will be the dilepton analysis, a few words about the detector, doing b-physics with the silicon vertex detector, the SVX b-tag analysis, the cross section and the mass analysis.

We have been doing collider physics for a long time. Collisions were detected in 1985. Our first Physics run with an integrated luminosity of 25 nb^{-1} took place in 1987-88. Our next run (1988-89) with a luminosity of 4 pb^{-1} resulted in a limit on the top mass of greater than 91 GeV/c^2.[2] This limit was primarily determined from the number of dilepton events. In Run 1a (1992-93), luminosity = 19.3 pb^{-1}) we presented evidence for the existence of the top quark [3]. This evidence depends on the observation of dilepton events, and lepton plus 3 or more jets, where one of the jets is tagged as a b jet. The b jet is tagged using either SVX tracking information to find a displaced vertex or a soft lepton tag (SLT) indicating a b decay (b → l ν X, or b → c → l ν X). Earlier this year we reported the observation of the top quark[1]. This observation is also based on the dilepton and b-tag (SVX and SLT) modes but with better statistics. This talk refers to the same sample as reported in ref. [1] with a combined luminosity from run 1a and 1b of 67 pb^{-1} (note that as of June 12 the combined luminosity was over 100 pb^{-1}).

The Tevatron collider luminosity has increased with each run. The reader interested in the status of the Tevatron should read reference[4]. The design luminosity for the Tevatron was 10^{30} $cm^{-2}s^{-1}$. Today the typical luminosity is between 1.4 and 2.0 × 10^{31} $cm^{-2}s^{-1}$. The standard expression for the luminosity is given in figure 1. In the formula ϵ is the emittance. For run 1b we have typical values of N_p = 22.5 × 10^{10} protons/bunch, $N_{\bar{p}}$ = 6.5 × 10^{10} antiprotons/bunch, the number of bunches is 6, the typical value for the form factor (F) is 0.62, the proton (antiproton) emittance is 22 (14) π mm-mrad and the value of β^* at the interaction point is 35 cm. Note these typical values yield a luminosity of 1.9 ×$10^{31}$$cm^{-2}s^{-1}$.

The ultimate phase space density is limited by the beam-beam tune shift which

Accelerator Parameters

$$L = N_B f_0 \frac{N_p N_{\overline{p}}}{4\pi\sigma_V\sigma_H} F$$

- N_B Number of Bunches
- f_0 Revolution frequency
- N_p Protons/Bunch
- $N_{\overline{p}}$ Anti-Protons/Bunch
- F Form Factor

$$\sigma_V^2 = \left(\frac{\epsilon_p^V + \epsilon_{\overline{p}}^V}{2}\right) \frac{\beta_V^\star}{6\pi\beta\gamma}$$

$$\sigma_H^2 = \left(\frac{\epsilon_p^H + \epsilon_{\overline{p}}^H}{2}\right) \frac{\beta_H^\star}{6\pi\beta\gamma}$$

Figure 1: Expression for the luminosity.

at the present operating point is 1.5×10^{10} particles per π mm-mrad. During run 1b the single bunch proton (antiproton) phase space density is 1.0 (0.6) $\times$ 10^{10} particles per π mm-mrad. This indicates that to increase the luminosity we need to increase the number of bunches. After the main injector is completed in 1998, we will start run 2 in early 1999. For that run we will have 36 bunch operation resulting in a typical luminosity of $2.0\times$ 10^{32} cm^{-2}s^{-1}. These estimates may be low and indeed luminosity a factor of 5 higher may be possible.[5]

As shown earlier, it has taken a long time for us to observe the top quark. The reason for this is obvious, namely the low cross section for $t\overline{t}$ production . The fact that we have finally been able to observe the top quark is due to the high luminosity achieved by the accelerator. The $p\overline{p}$ total cross section (80.03 ± 2.24 mb) is more than 10^{10} larger than the top cross section ($6.8^{+3.6}_{-2.4}$ pb).[1] Indeed for the dilepton mode there is an additional factor of 100. Only about 5% of the $t\overline{t}$ decay via the dilepton mode, and of these we are only able to detect about 1 in 5.

The search for top has been CDF's top priority for many years. But clearly we also have tried to do as much other physics as possible. At the present time we are writing out data at the rate of 6 Hz, where each event is approximately 100 Kbytes. As of April-1995 we had written out over 30 M events. The top analysis is done from an express line. The number of events in the express line is about 2 M, which corresponds to $2\times$ 10^{11} bytes.

2 Dilepton analysis

The branching ratio for the three decay modes of the top are 44% for the hadronic, 44% for the lepton plus jet, and only 11% for the dilepton. Although we are making progress on looking at the all hadronic mode, this talk will refer to only the lepton plus jet and dilepton modes. At this time we will report only on modes involving an electron or a muon. Thus the relevant branching fractions are 29.6% for the lepton plus jet and 4.9% for the dilepton modes. We look at the dilepton mode by requiring two oppositely charged high P_T leptons and a neutrino (large $\not{E}_T$).

A P_T threshold of 20 GeV for each lepton is chosen to preserve a large portion of the top signal and to suppress the backgrounds. For central electrons we apply several cuts to eliminate hadrons. These include a cut on the ratio of the hadronic to electromagnetic energy of the cluster (HAD/EM), the ratio of the cluster energy to track momentum (E/P), a comparison of the lateral shower profile (L_{sh}) in the calorimeter cluster with that of test beam electrons, the distance between the extrapolated track position and strip chamber shower position measured in the ϕ and z views, and a χ^2 comparison of the strip chamber shower profiles with those of test beam electrons. In general one lepton requires a tight cut and the other a loose cut. At least one central lepton in each event must pass a track isolation cut I_{track} < 3 GeV/c where I_{track} is the sum of the P_T over all tracks in a cone of radius 0.25 (in $\eta - \phi$ space) centered on the lepton track. The trigger requirements are very efficient as one has two chances to pass a single high P_T lepton trigger. For details that also include plug electron and muons, see reference [3]. Conversions and same sign dileptons are also removed. There are 3 topology cuts. The first eliminates backgrounds from Z decays, by cutting on the dilepton invariant mass. The second cut requires $\not{E}_T > 25$ GeV and removes backgrounds from $Z \rightarrow \tau\tau$, $b\bar{b}$ and lepton misidentification. For events with $\not{E}_T < 50$ GeV, the third cut requires that $\Delta\phi(\not{E}_T$, lepton) $> 20°$ and $\Delta\phi(\not{E}_T$, jet) $> 20°$, where $\Delta\phi(\not{E}_T$, lepton or jet) is the azimuthal angle between the $\not{E}_T$ and the direction of the nearest lepton or jet. Finally we require two jets with $\eta < 2.0$ to have uncorrected transverse energy greater than 10 GeV. The results of all these cuts is a dilepton detection efficiency of 17.3 ± 0.15 %.

From the 2M express line events, the number of high P_T isolated lepton events is about 48K electrons and 32 K muons. The number of events as a function of cuts is given in table 1. After all the cuts there are no ee events, two $\mu\mu$ events, and five $e\mu$ events.

Table 1: Dilepton data for 67 pb^{-1}

	ee	$\mu\mu$	$e\mu$
Lepton ID	2146	2220	39
Same Sign	2118	2211	29
Isolation	2079	2148	25
Z Mass	215	233	25
Missing E_T	5	4	9
2-jet (10 GeV)	0	2	5

Five different physics processes are considered as contributing to the dilepton background. These are Drell-Yan, $p\bar{p} \rightarrow Z \rightarrow \tau\tau$, fake leptons, $p\bar{p} \rightarrow$ WW, and $p\bar{p}$

$\rightarrow b\bar{b}$. The total background is 1.3 ± 0.3 events. To be conservative in estimating a signal for top, we have removed an event labeled $\mu\mu\gamma$. This event could be a radiative Z decay as the invariant mass of the $\mu\mu\gamma$ is 86 GeV/c^2. However, this event is included when calculating a cross section (see section 6).

In summary, 6 dilepton events are observed. The expected background is 1.3 ± 0.3 events. The probability of the background to fluctuate up to the signal for the dilepton events is 2.7σ. Three of the events contain a total of 5 btags, compared with an expectation of 0.5 if the events are from background. We expect 3.6 tags if the events are from $t\bar{t}$.

3 Detector

The CDF detector currently consists of a 1.4 Tesla superconducting solenoid with tracking detectors inside it. Calorimeters (electromagnetic and hadronic) are located outside the magnet and in the forward region. Muon detection is provided by chambers located outside the calorimeters in the central region. A silicon vertex detector located just outside the beam pipe is used for secondary vertex identification.[6]

For run 1b a new ac-coupled, four-layer silicon vertex detector with radiation-hard electronics, was installed. This detector is 51 cm long and has top b-tag efficiency of 42%. For run 2 we will have a new 96 cm long silicon vertex detector with an efficiency of about 80%. This detector will provide coverage in both the r-ϕ and r-z views. Detailed information about the CDF upgrade plans is found in reference[7].

In addition to the SVX upgrade the present gas calorimeters will be replaced with new scintillator based calorimeter. Green wavelength shifting fibers will be inserted into scintillating tiles. This upgrade increases the radiation hardness of these detectors so that they will operate at a luminosity of 10^{32} cm^{-2} s^{-1}. The new electromagnetic calorimeter will contain an embedded position detector at shower maximum to improve electron identification and π/γ separation. As seen in the figure the new detector is more compact.

A scintillating fiber tracker will be added between the SVX and the CTC (Central Tracking Chamber). This device will increase the region in which we can reconstruct tracks (rapidity coverage will increase from $\mid \eta \mid < 1.4$ to 2.0).

The new running conditions will require many changes. The shorter bunch spacings for run 2 (395 ns or even 132 ns) will require many upgrades in electronics. The increase in luminosity to 2×10^{32} cm^{-2} s^{-1} raises many interesting question relating to occupancy in the CTC. Many improvements will be needed to both the data acquisition and offline computing before we are able to process data under run 2 conditions.

4 Silicon Vertex Detector b-Physics

Much effort has been devoted to understanding and simulating the SVX detector.[8] Our understanding includes the primary ionization ($\frac{dE}{dx}$ of the ionizing particle forming electron hole pairs) the secondary ionization (δ ray) and noise. Good agreement is obtained between an inclusive electron sample (95% $b\bar{b}$) and a $b\bar{b}$ Monte

Carlo. The ratio of data to Monte Carlo efficiencies is 0.96 ± 0.07. We have also used the SVX to do b-physics.[9]

5 SVX Analysis

The efficiency for tagging at least one b quark in a $t\bar{t}$ event with 3 or more jets is determined from Monte Carlo simulations to be 42 ± 5%. This is a considerable improvement over the SVX b-tagging for run 1a (22 ± 6%). The reasons for the improvement are an improved SVX (ac-coupled detectors and radiation harden electronics), an improved vertex finding algorithm, and fixing a previous bug in the Monte Carlo simulation, and better statistics in the Monte Carlo and also in the data used to check the Monte Carlo.

Figure 2 shows as circles the number of W + n jet events before tagging. There

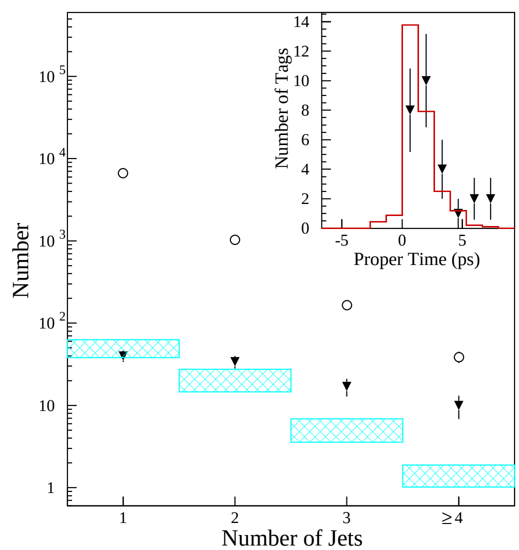


Figure 2: Number of events before SVX tagging (circles), number of tags observed(triangles) and expected number of background tags (hatched) versus jet multiplicity. The inset shows the secondary vertex proper time distribution for the 27 tagged jets in W + $\geq$ 3 jet data (triangles) compared to the expectation for b quark jets from $t\bar{t}$ decay.

are 203 W + n $\geq$ 3 jet events. The number of W + n jet events with SVX tags are shown as triangles. The estimated background is shown as a hatched region. There are 27 SVX tags for W + n $\geq$ 3 jets. The background is calculated to be 6.7 ± 2.1 for W + n $\geq$ 3 jets. The insert shows the secondary vertex proper time distribution for the 27 tags. The solid curve shows the expected proper time distribution for b quark jets from a $t\bar{t}$ Monte Carlo. Clearly the distribution agrees with expectations.

The largest background for SVX tagging is caused by a gluon jet in a W event splitting into a heavy flavor pair. The second largest background is a "Mistags" where a light quark jet in a W event is tagged as a b jet due to resolution smearing or errors. Other backgrounds such as flavor excitation (sg → Wc), WW, WZ, Z→

$\tau\tau$ and non-W $b\bar{b}$ are also significant.

The most reliable method is to use Monte Carlo simulations for all processes except for the "Mistags". The "Mistags" are estimated using the negative decay length tags observed in di-jet samples. The sum of all the backgrounds is 6.7 $\pm$ 2.1 tags.

6 Cross Section

In this section we give the results for the number of events obtained in the dilepton, SVX and SLT channels. The results are presented for both run 1a and the present sample from run 1a + 1b (67pb^{-1}). Our present result for the background to fluctuate up to reproduce the signal is 4.8σ. This result is based on 6 dilepton events and 37 b-tagged events. The relevant numbers are 6 dilepton events with a background of 1.3 $\pm$ 0.3 events, 27 SVX tags (in 21 events) with a background of 6.7 $\pm$ 2.1 tags and 23 SLT tags (in 22 events) with a background of 15.4 $\pm$ 2.0 tags.

Fig. 3 gives a new preliminary value for the $t\bar{t}$ production cross section of $7.6^{+2.4}_{-2.0}$ pb. This number is based on all three measurements (dilepton, SVX, SLT). Our

*** Cross Section (Preliminary)**

$$\sigma = \mathbf{7.6}\ ^{+2.4}_{-2.0}\ \mathbf{pb}$$

Dilepton Channel

Lepton Plus Jets Channel

SVX Silicon vertex b-tagging

SLT Soft Lepton b-tagging

- Run 1a + 1b Luminosity = 67 $\pm$ 4.85 pb^{-1}

DL 7 events Background 1.3 $\pm$ 0.3

$\epsilon = 0.78 \pm 0.08$ %

$\sigma = 10.9\ ^{+5.9}_{-4.5}$ pb

SVX 21 events Corrected-Background 5.5 $\pm$ 1.8

$\epsilon = 3.38 \pm 0.87$ %

$\sigma = 6.8\ ^{+2.9}_{-2.3}$ pb

SLT 22 events Corrected-Background 14.7 $\pm$ 2.2

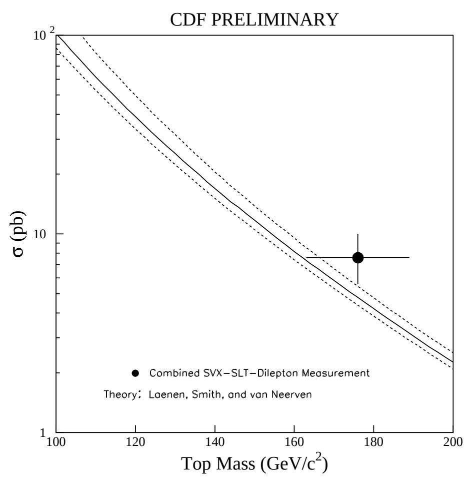
$\epsilon = 1.73 \pm 0.29$ %

$\sigma = 6.3\ ^{+5.0}_{-4.1}$ pb

Figure 3: The cross section (preliminary) from run 1a + 1b from 67 pb^{-1} using dilepton, SVX and SLT data.

"total efficiency $\times$ acceptance " for the SVX of 3.38% is the product of the branching ratio (29.6%), the lepton plus jets efficiency of 8.1% and the SVX efficiency of 42%. Similarly the SLT "total efficiency $\times$ acceptance" of 1.73% is the product of the branching ratio (29.6%), the lepton plus jets efficiency of 8.1% and the SLT efficiency 22%.

The cross section is compared to the theory [10] (next-to-next-to leading order) in Fig. 4. The new value is clearly a little higher than the theory value but is



$$\sigma(t\bar{t}) = 7.6\ ^{+2.4}_{-2.0}\ pb$$

Figure 4: The preliminary CDF data point and a theory curve from Laenen *et al*.

consistent with it given the large errors.

7 Mass Analysis

The process

$$p\bar{p} \rightarrow t\bar{t} + X$$

is kinematically constrained. In this five vertex system we have assumed that the initial $p\bar{p}$ system has a net momentum of zero and an energy of 1.8 TeV. We further assume the mass of t and $\bar{t}$ are the same. Further details of the fitting method are given in reference [3]. From the measured jet energies we must correct for missing energy (μ's or neutrinos) as well as for energy that is outside the jet cone we are using (ΔR = 0.4). Reference [12] contains further information on jet corrections. The system of equations yields an overconstrained system of 20 equations in 18 unknowns (2C-fit). As we do not measure the longitudinal component of the energy, there are two possible solutions for the P_Z of the neutrino. There are 24 possible combinations because you select b_1 from the 4 jets, then you select b_2 from the remaining 3 jets, and you have two choices for the P_Z of the neutrino. In most cases these two solutions are almost identical with regard to the mass of the top quark. Of the 24 different combinations the one with the lowest χ^2 is selected. If a b is tagged the number of solutions is only 12 and if two b's are tagged the number of solutions is only 4.

The top mass has been computed by three independent groups within CDF using slightly different methods. The results using the MINUIT fitter are presented here for the pretagged sample (with no b-tagging) of 88 events. Much the same mass is obtained when the top background is constrained (176.1 $\pm$ 8.6 GeV/c^2) and when it is not (174.6 $\pm$ 7.7 GeV/c^2). The shape of the fitted background is obtained from the VECBOS Monte Carlo. The reconstructed mass spectrum is given in Fig. 5. The figure also shows the constrained background fit. It is clear

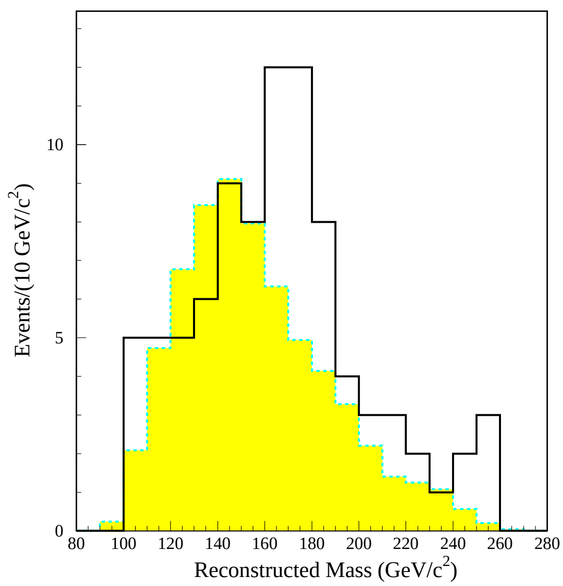


Figure 5: The reconstructed mass of the pretagged sample. The background is constrained to 65 events.

that there is a signal of top events. The distribution is consistent with the predicted mix of approximately 30% $t\bar{t}$ and 70% W + jet background (VECBOS [11]).

However the situation is much clearer when we use the b-tagged sample (19 events). This b-tagged sample uses both the SVX and SLT tags. The mass obtained from the MINUIT fitter is 175.6 $\pm$ 7.8 GeV/c^2 for the constrained fit and 175.0 $\pm$ 6.7 GeV/c^2 for the unconstrained fit. The reconstructed mass spectrum is given in Fig. 6. The largest systematic error is the absolute jet energy scale (4.4%). The accuracy is determined from photon-jet and Z-jet balancing.

Our top mass measurement can be combined with our recent measurement from run 1a of the W mass. The results are presented in Fig. 7. We see that almost no limitations are placed on the Higgs mass. The situation will improve considerably when run 2 is complete. Run 2 is expected to have an integrated luminosity of more than 1000 pb^{-1} (best estimate is 2000pb^{-1}). For an integrated luminosity of 1000pb^{-1} the estimated uncertainty in the W mass is expected to be 45 MeV/c^2 and the uncertainty in the top mass is expected to be 4 GeV/c^2.

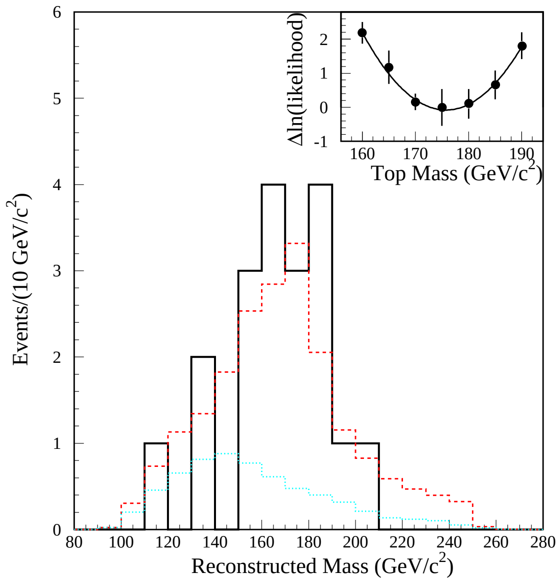


Figure 6: The reconstructed mass of the tagged sample. Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for M_{top} = 175 GeV/c^2 (dashed), with the background constrained to the calculated value of $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

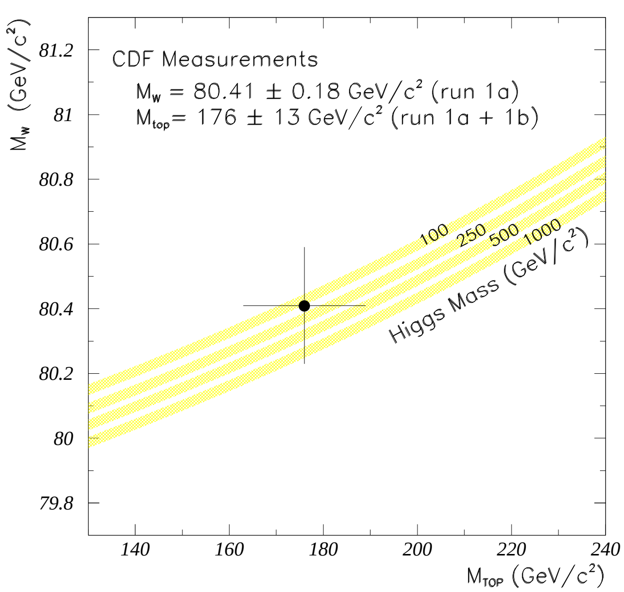


Figure 7: M_W versus M_{TOP} as measured by CDF (May 1995). For run 2 we estimate the uncertainty in the top mass will be 4 GeV and the uncertainty in the W mass will be 45 MeV.

I will present additional information on the CDF top analysis on May 25 ("Kinematics of the $t\bar{t}$ events in W + Jets at CDF"). I will show the reconstructed mass of the $t\bar{t}$ system for a b tagged sample of 19 events.

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