Status of the CDF Top Quark Search

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1. The CDF Experiment
2. CDF Dilepton Search
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7. Conclusions

Workshop on the Origin
of Fermion Masses and Couplings
Fermilab
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Why Do We Need a Top Quark

The Standard Model of Elementary Particle Physics

- Three "generations" of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

"Isospin" doublets that dictate particle interactions

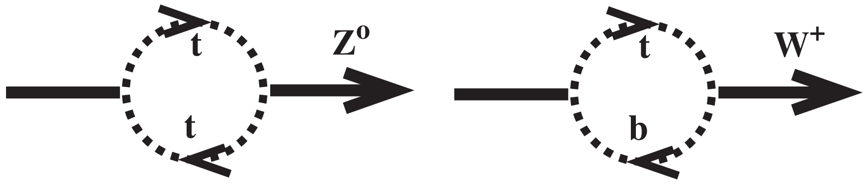
- Forces carried by bosons

Electromagnetic force	γ
Strong force	eight gluons
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Gravity	gravitons

SM Only Works with 3 Generations

If top doesn't exist, the SM is in deep trouble

- Corrections to $W^{\pm}$ and Z° masses depend on heaviests fermions



  - LEP measurements on the Z resonance require

$$M_{top} = 178 \pm 11^{+18}_{-19} \text{ GeV/c}^2$$

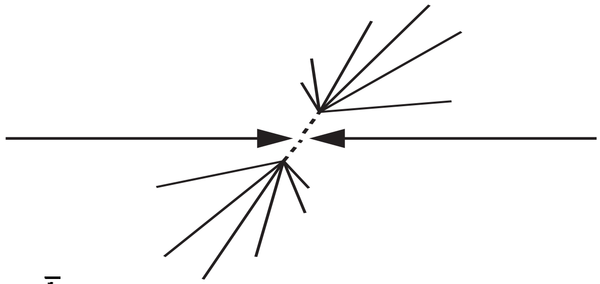
- Properties of the bottom quark imply that its partner exists
  - Weak force predicts asymmetry in $e^+e^- \rightarrow b\bar{b}$
  - Singlet bottom quark fails FCNC constraints

- b quark "mixing" could not occur

SM Predictions

Searches at e^+e^- Colliders have ruled out "light" top

- data from LEP requires $M_{top} > 46$ GeV/c^2 at 95% CL
- Independent of how top decays



Width of $W^\pm$ boson rules out $W^+ \to t\bar{b}$

- $M_{top} > 62$ GeV/c^2 at 95% CL

Searches at $p\bar{p}$ colliders at CERN and Fermilab

- searched for a "Standard Model" top
- $M_{top} > 131$ GeV/c^2 at 95% CL (D0 Collab).

Searching for Top

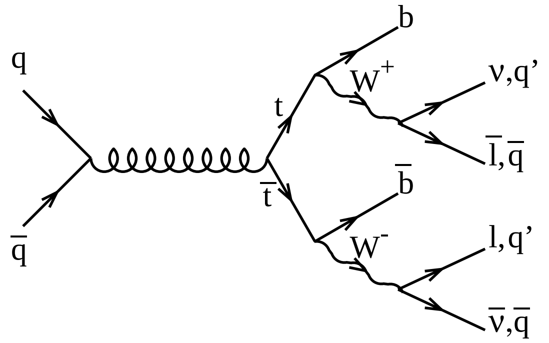
SM top quarks decay primarily via the weak force

$$t \rightarrow W^+ b$$

$\quad\quad\quad\quad \llcorner\!\!\longrightarrow u\bar{d}$ or $c\bar{s}$

$\quad\quad\quad\quad \llcorner\!\!\longrightarrow e^+\nu_e$ or $\mu^+\nu_\mu$ or $\tau^+\nu_\tau$

In proton-antiproton collisions,



This results in two, potential signatures

- Dilepton events with two, energetic $e^\pm$ and $\mu^\mp$
- Lepton + Jet events with at least one b quark

The CDF Experiment

CDF is detector designed to study $\overline{p}p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Large 5000 ton detector

Collaboration consists of

- 35 institutions from US, Japan, Italy, Canada and Taiwan
- 440 physicists

Took our first data in 1987

- 0.03 pb^{-1} in 1987
- 3.7 pb^{-1} in 1988-89
- 19.3 pb^{-1} in 1992-93

1992-93 Collider Run

Took data at the Tevatron Collider in 1992-93

- scanned $\sim 1 \times 10^{12}$ collisions
- Collected 16×10^{6} events on tape
- Integrated luminosity of 19.3 pb^{-1} (Run Ia)

Most sensitive dataset acquired to date

- For a top quark with a mass of 160 GeV/c^2
  - cross section of 8.2 pb $\Rightarrow$ 160 produced $t\bar{t}$ events
  - expect to observe 1.3 dilepton events
  - expect to observe 3.5 lepton + jet events

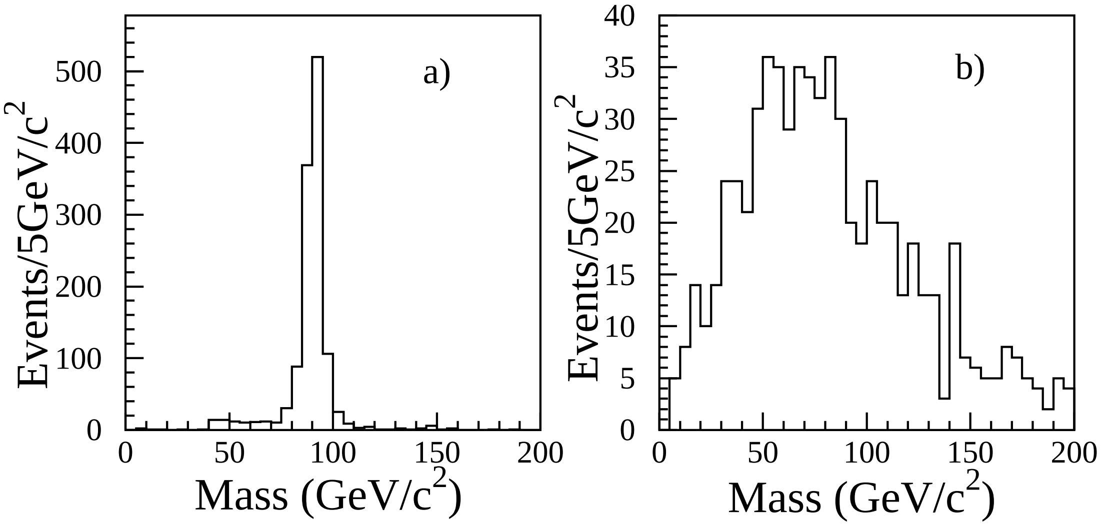
Dilepton Top Quark Search

$t\bar{t}$ decaying into 2 leptons create unique signature

- Two charged leptons from $W^{\pm}$ decay
- Imbalance in total energy due to undetected neutrinos
- Two jets from bottom quarks

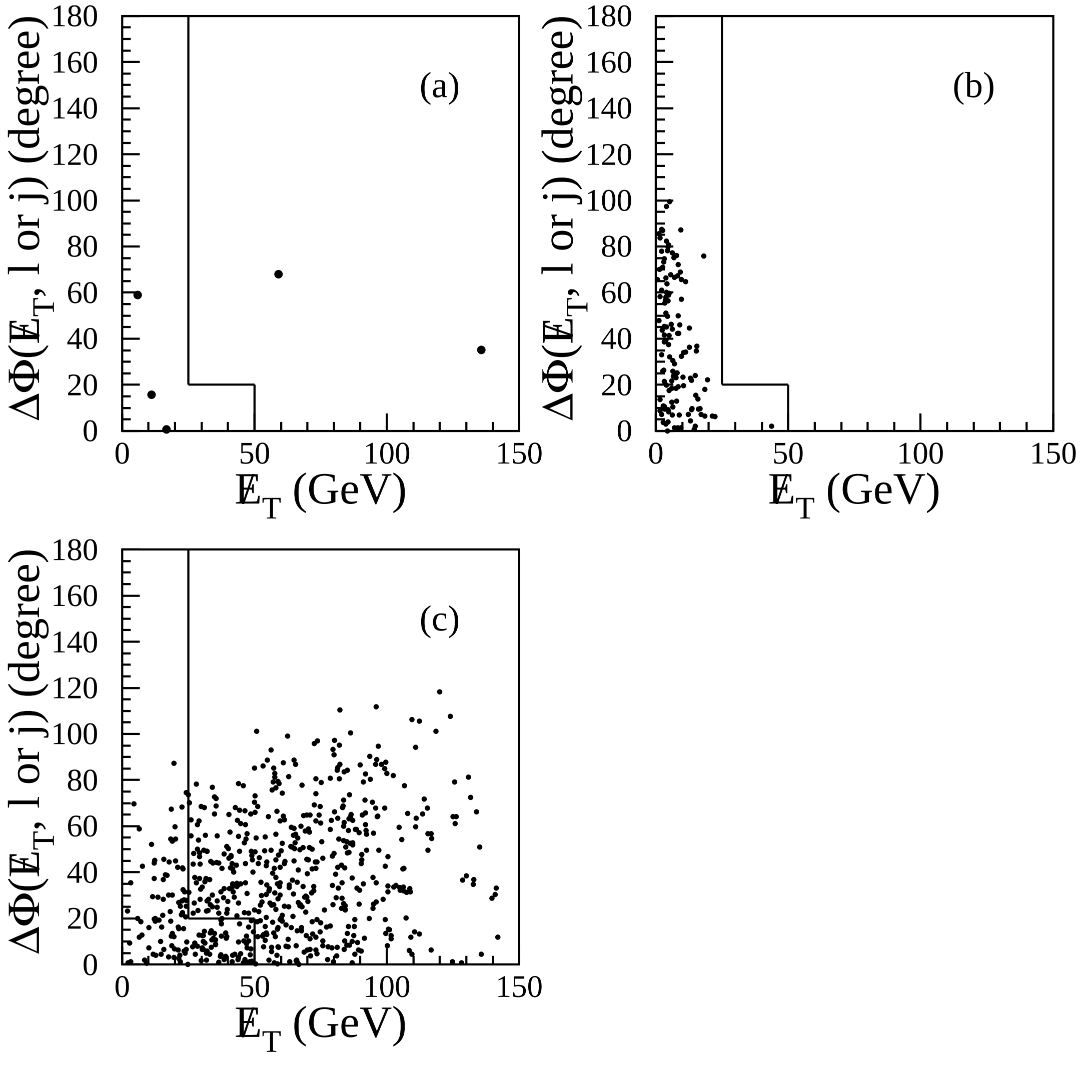
Performed a search requiring

- Two clean lepton candidates with $P_T > 20$ GeV/c
- Missing transverse energy $\not\!\!E_T > 25$ GeV
- Require two jets with $E_T > 15$ GeV and $|\eta| < 2.0$
- Reject specific backgrounds (e.g. Z°)



Significant dilepton background is Drell-Yan production

- $\not\!\!E_T$ signature created by mismeasured jet
- Harden $\not\!\!E_T$ cut if correlated with jet



Backgrounds in Dilepton Channel

Have measured the rate of events from non-top sources

- Have used data to measure these rates
- Cross-checked using $Z^\circ \to e^+e^-$ and $Z^\circ \to \mu^+\mu^-$
- Consistent with theoretical calculations

Background	**e**μ	**ee**, $\mu\mu$
$Z \to \tau^+\tau^-$	0.07 ± 0.02	0.06 ± 0.02
One or both leptons fake	0.03 ± 0.03	0.04 ± 0.03
$b\bar{b}$	0.04 ± 0.03	0.05 ± 0.03
WW, WZ and ZZ	0.10 ± 0.04	0.06 ± 0.02
Drell-Yan		$0.10^{+0.23}_{-0.08}$
Total	0.24 ± 0.06	$0.31^{+0.24}_{-0.10}$

Expect $0.56^{+0.25}_{-0.13}$ background events

Observe **two** events in sample

- Both events have electron and muon candidates
- One has signature of b quark jet

Background sources are small

- Drell-Yan production $\Rightarrow$ 0.20 events
- WW, WZ production $\Rightarrow$ 0.16 events
- Total backgrounds are $0.56^{+0.25}_{-0.13}$ events

On the other hand, rate from top depends on top mass

M_{top} (GeV/c^2)	Number of events
120	3.7
140	2.2
160	1.3
180	0.7

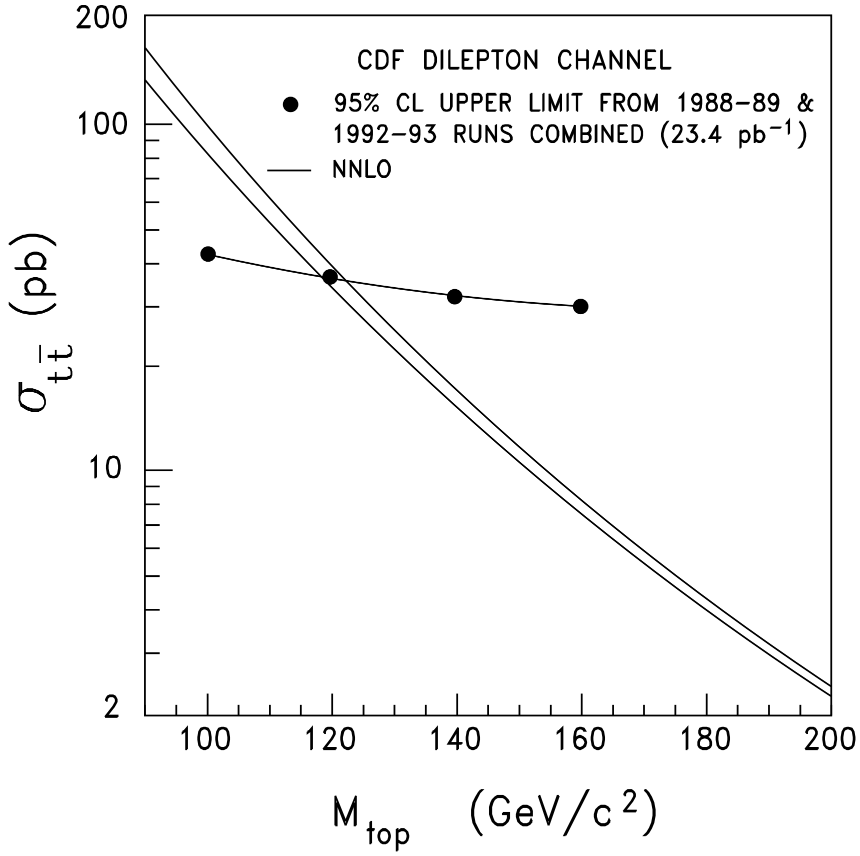
Probability 0.56 events fluctuates to ≥ 2 events is 12%

$\Rightarrow$ Not statistically significant

Mass Limit from Dilepton Data

Can use dilepton data to exclude low mass top

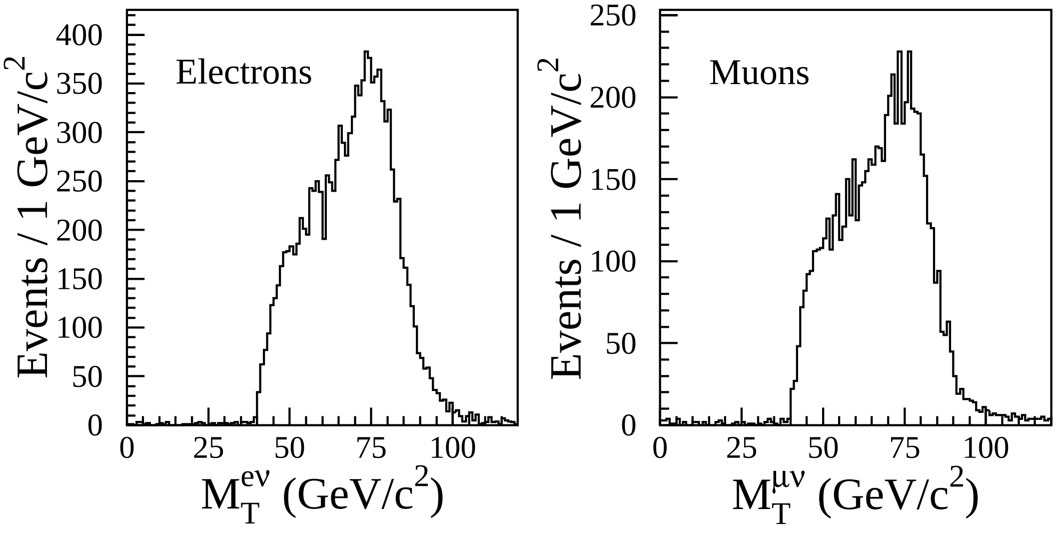
- In this case, remove jet requirement
  - Jet efficiency less certain for $M_{top} \sim 100 - 120$ GeV/c^2
  - No additional events are added to sample
- Add 3.7 pb^{-1} from 1988-89 data run (no events)
- Backgrounds increase to 3.0 ± 0.6 events
- Assume 2 events are top and set limit on σ_{top}



Lepton + Jets + B Tag Search

Decay mode with the greatest sensitivity is "lepton+jets"

- About 30% of $t\bar{t}$ events decay this way
- Look for one high P_T lepton
- Require $\not{E}_T > 25$ GeV
- Have 11,900 $e\nu_e$ and 7,000 $\mu\nu_\mu$ candidates



$\boxed{\text{W + Jet Sample}}$

Require ≥ 3 jets (from other W decay and b quarks)

- $E_T > 15$ GeV and $|\eta| < 2.0$
- Find 52 events with these criteria

We have estimated various background sources:

Background	Number of Events
Fake leptons and $b\bar{b}$	5.2 ± 2.6
WW, WZ and ZZ	2.6 ± 1.2
$Z \to \tau\tau,\ ee,\ \mu\mu$	4.4 ± 0.9
Total	12.2 ± 3.1

QCD W+jets production is largest expected background

M_{top} (GeV/c^2)	Number of Events
120	39 ± 6
140	22 ± 3
160	12 ± 2
180	6.6 ± 0.7
W+jets	50^{+16}_{-8}

Reject W+jets using B tagging

B Tagging Techniques

We use two properties of b quarks to identify them

1. "Long" b lifetime – $c\tau \sim 450$ microns

   - Use the Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 20% of $t\bar{t}$ events to have at least one SVX tag

2. About 20% of b's decay via

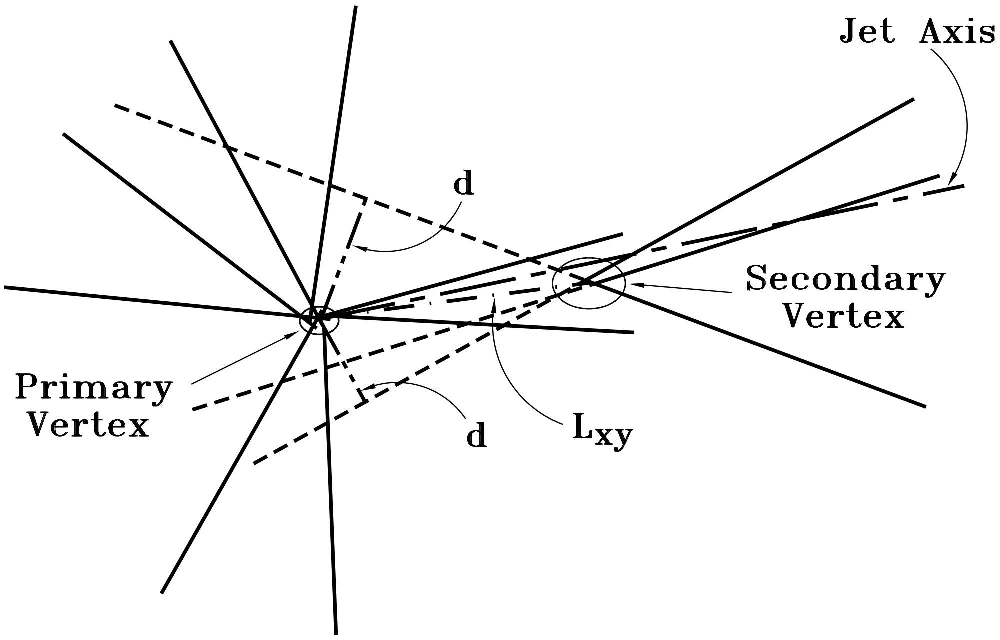
$$b \to e^- \nu_e X \quad \text{and} \quad b \to \mu^- \nu_\mu X$$

   - Look for jets with "soft" leptons in them
   - Call these soft-lepton tags (SLT's)
   - Expect about 15% of $t\bar{t}$ events to have at least one SLT tag

SVX B Tags

SVX tag requirements are

- at least 2 tracks with impact parameter $d > 3\sigma$
- track $P_T > 2$ GeV/c
- the tracks are consistent with coming from a common vertex



Used control samples to measure the tagging efficiency and fake rate

- inclusive electrons enriched in $b \to e^+ \nu_e X$ decays
- $B \to J/\psi X, \quad J/\psi K^{\pm}, \quad J/\psi K^*$ decays
- "generic" jet sample

Soft Lepton Tagging

Identify muon or electron from b hadron decay

- Require lepton $P_T > 2$ GeV/c
- Require electron to satisfy standard cuts
  - Use dEdx measurement in CTC to reject pions
  - Require muon candidate to have good quality muon stub

Studied SLT tagging using

- photon conversions for electrons ($\gamma \to e^+e^-$)
- $J/\psi \to \mu^+\mu^-$ decays
- generic jets to obtain fake rates

Measured efficiency and fake rates

- Efficiency is 0.152 ± 0.023 for $M_{top} = 160$ GeV/c^2
- "Fake" tagging rate is $\sim 0.005 - 0.010$ tags/track

b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

- The $W + 1$ and $W + 2$ jet samples are ultimate control
  - Don't expect significant top contribution
  - Theory predicts low b hadron content

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+1 jet	15.8 ± 2.1	8	34.1 ± 3.3	33
W+2 jet	6.3 ± 0.8	8	9.9 ± 1.0	12
W+$\geq$ 3 jet	2.30 ± 0.29	6	3.1 ± 0.3	7

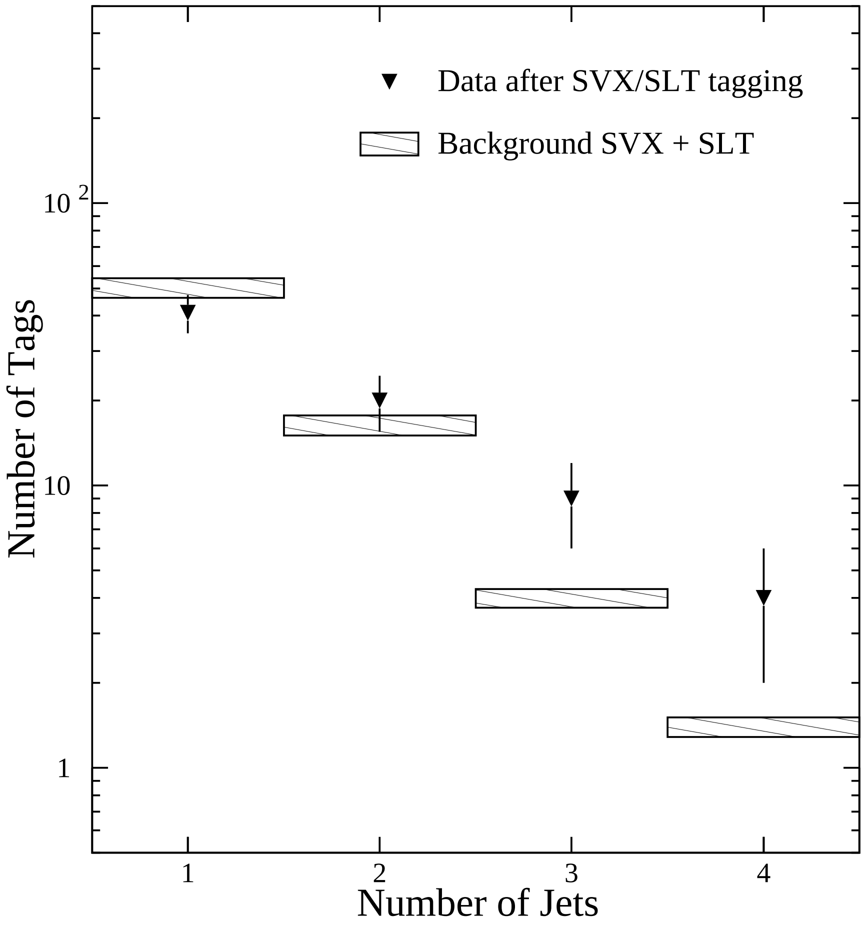
Observe 13 tags in 10 events

- 3 events are double-tagged
- Expected to see 5.4 ± 0.4 background tags

Summary of Jet Counting Experiment

We combine the SLT and SVX tagged data

- Compare with background estimates
- Observe 13 tags when we expect 5.4 ± 0.4 background



Features of Tagged Samples

Find that 3 events are "double tagged"

- 2 of these 3 have 2 different jets tagged
- Probability of 2 fake tags is very low
- Expect only 1.3 double-tagged events from background

One dilepton event has jet tagged as an SLT and SVX

- Expect only 0.13 events from purely background
- Expect 0.7 double tags if both events are $t\bar{t}$

Statistical Significance

Observe 12 events in total

- 2 dilepton events when we expect $0.56^{+0.25}_{-0.13}$
- 13 tags when we expect 5.4 ± 0.4
- 3 double-tagged events

Evaluated the probability of this assuming no top

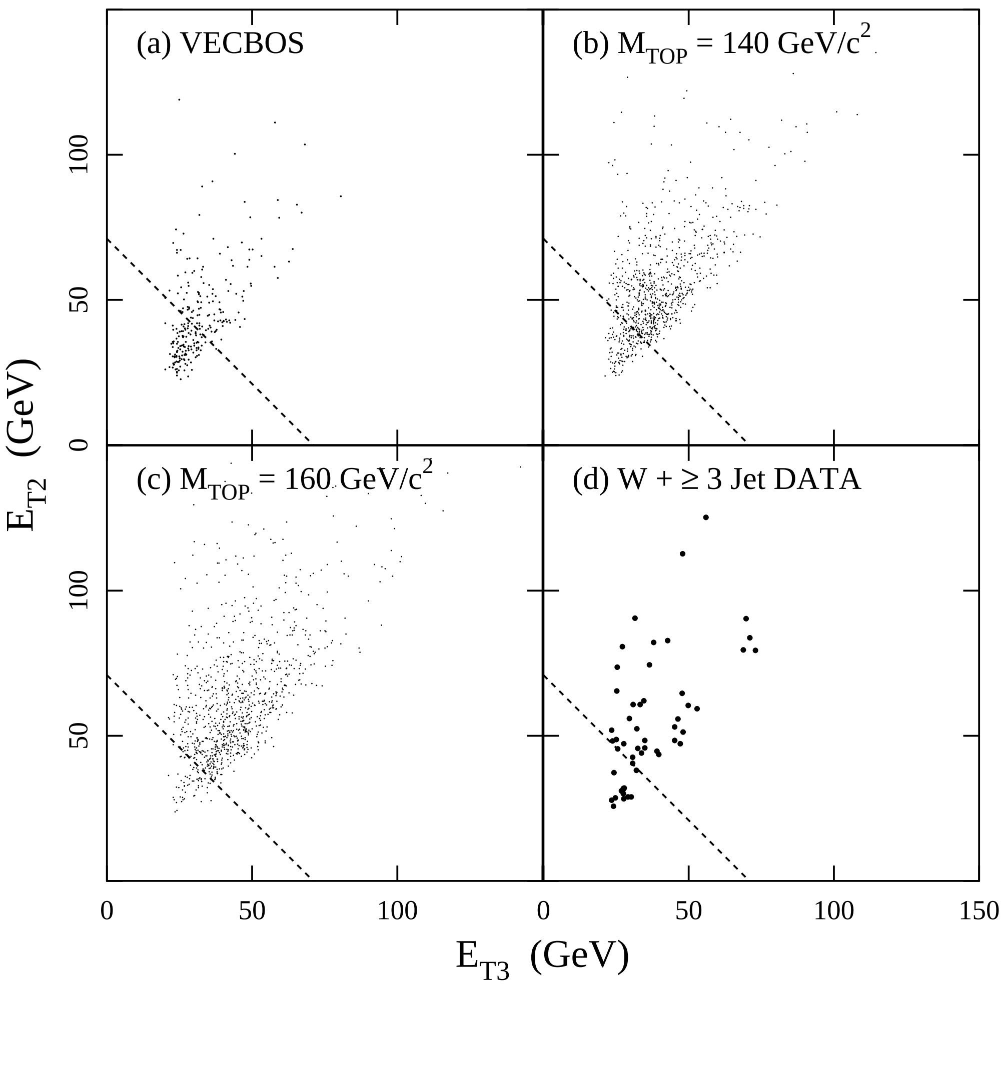
- Estimate the number of tags from the background sources
- Simulate our experiment assuming no top
- Count how often we would see at least the number of tags

Sample	Probability
6 SVX tags	0.032
7 SLT tags	0.038
13 tags + 2 Dilepton events	0.0026

Kinematic Features of Events

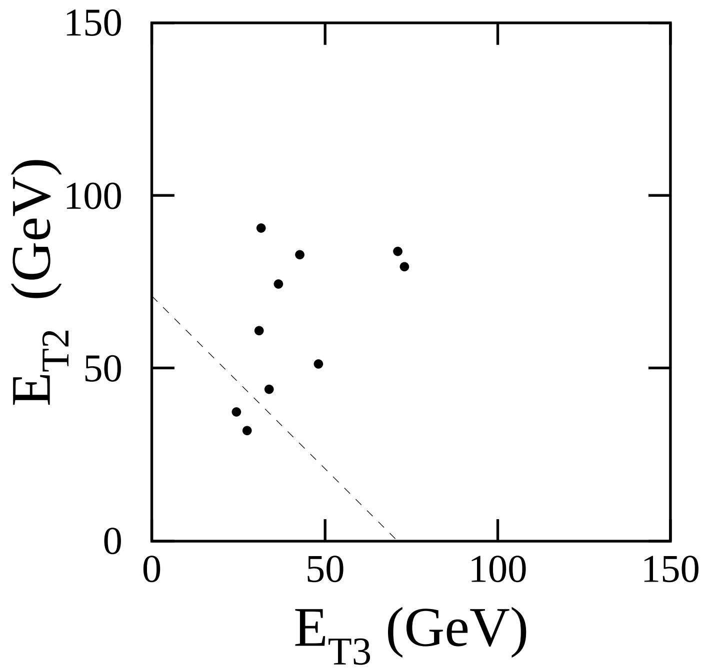
Examined the kinematics of these events

- Are there other features of data that indicate top?
- Good example are energies of second and third jet
- Need to trust MC calculations for W+jet and $t\bar{t}$ production



Kinematics suggest that of the 52 $W+\geq 3$ jet events

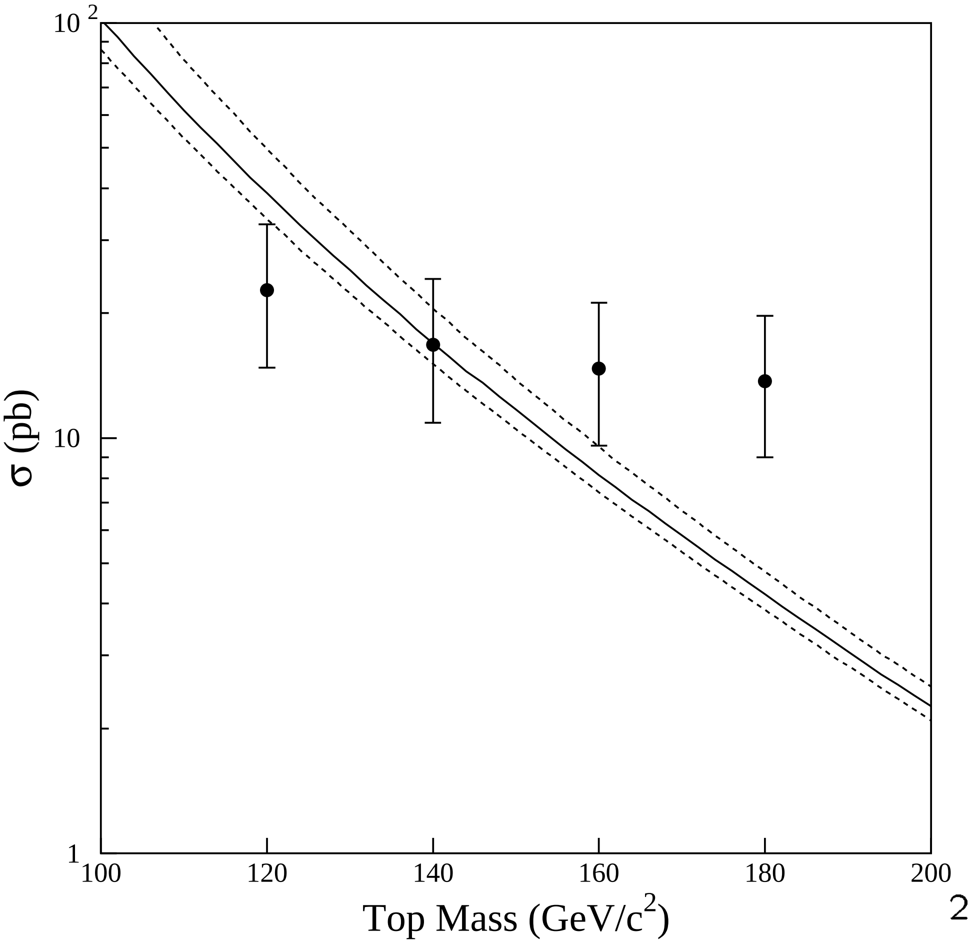
- ~ 20 events from $t\bar{t}$ production
- remainder mostly QCD $W+$ jets
- Confirmed by looking at E_{T2} versus E_{T3} for tagged sample



Cross Section for Top Production

Can use our data to estimate top quark cross section

- Subtract the expected backgrounds
  - 1.6 ± 0.7 and 1.5 ± 0.7 SVX and SLT background tags
- Perform a maximum likelihood fit to estimate $\sigma_{t\bar{t}}$



Measurement of Top Mass

We use event kinematics to estimate top quark mass

- Require events to have a fourth jet
- Combine all possible jet pairs to form $W \to q\bar{q}$
- Use b-tag information to identify b quark jet
- Fit events requiring kinematic constraints

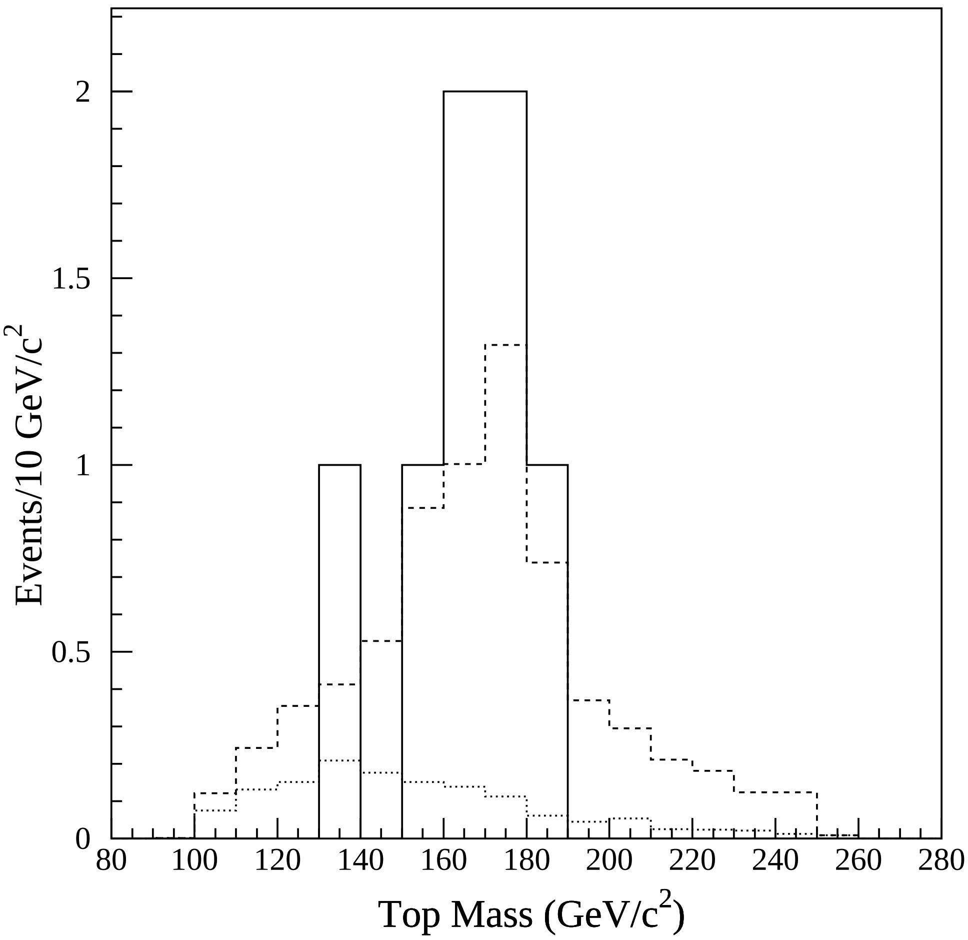
This selection leaves us with 7 tagged events

- Estimate background to be $1.4^{+2.0}_{-1.1}$ events
  - Primarily QCD W+jet

Procedure is dependent on theory predictions

Result of Mass Fits

The fitted mass for the 7 events is consistent with $t\bar{t}$

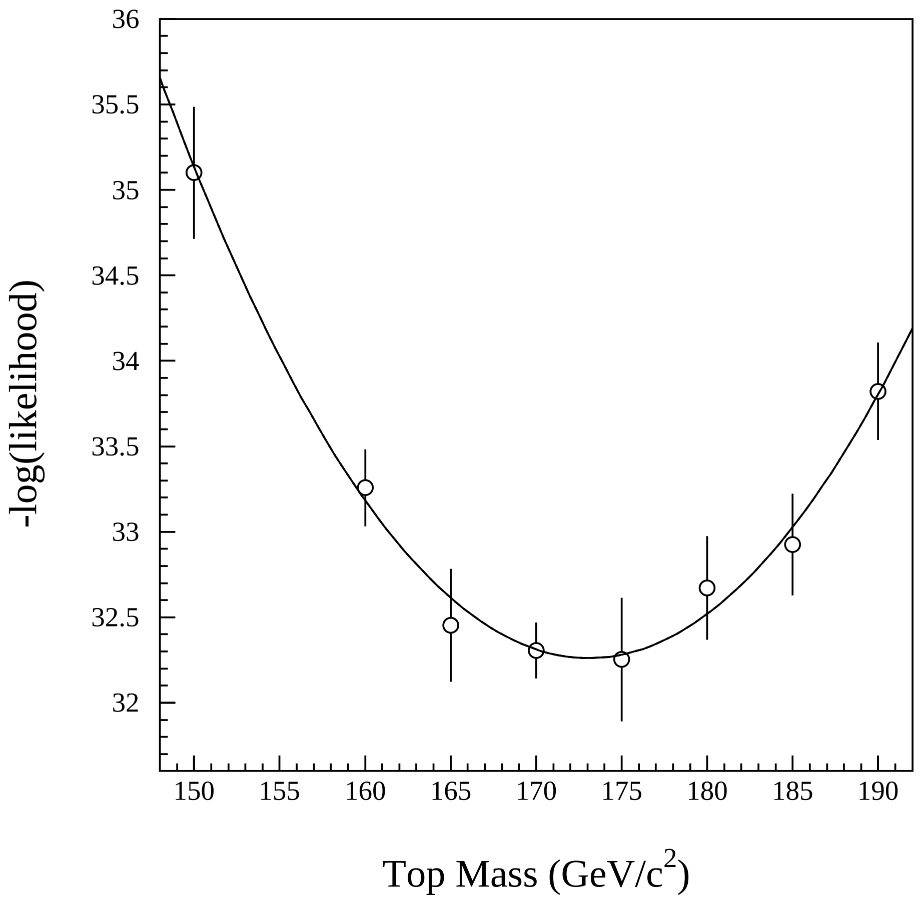


Fit the mass distribution to obtain

$$M_{top} = 174 \pm 10^{+13}_{-12} \quad \text{GeV/c}^2$$

Systematic error is dominated by uncertainties in

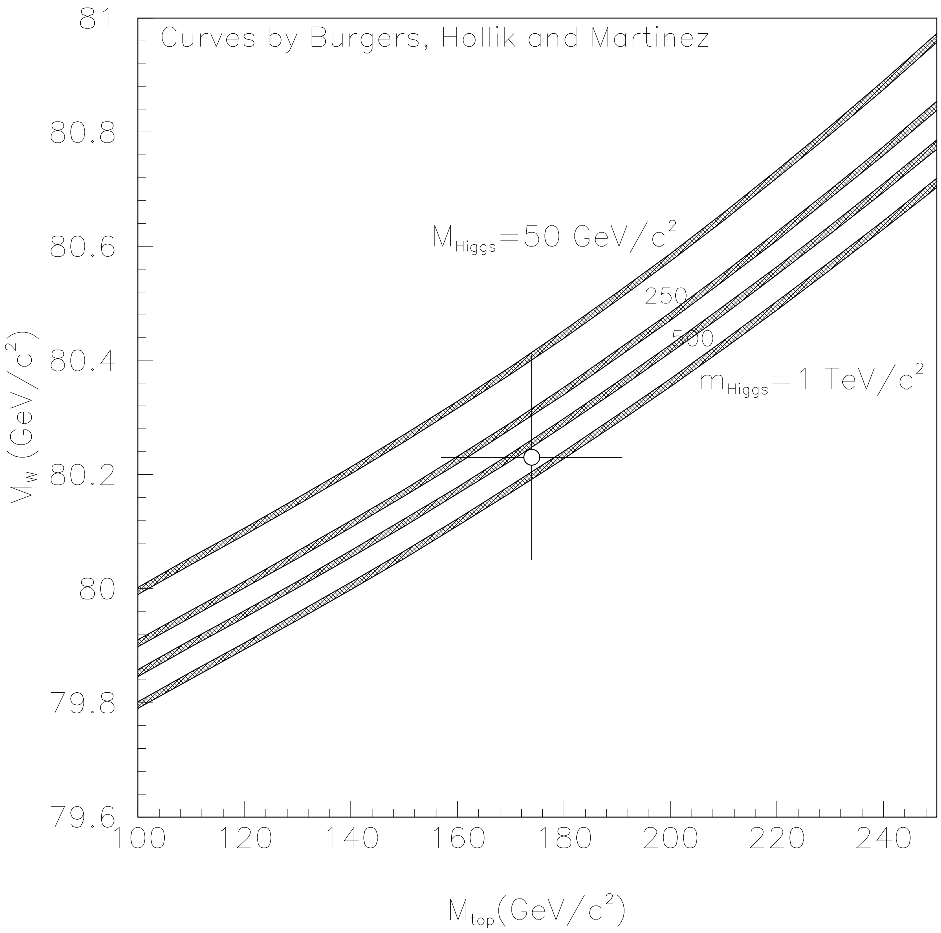
- Gluon radiation in $t\bar{t}$ production (4.4 GeV/c^2)
- Different background shapes ($\sim$ 5 GeV/c^2)



Physics Comments

Perhaps the most interesting immediate result is how heavy top appears to be

- In good agreement with indirect measurements
- Consistent with M_W measurements and SM



Are There Other Hypotheses?

We have considered a number of alternative hypothese

1. Are we seeing a b'?
   - Cross section would be too large
2. Are we seeing the Higgs boson?
   - Only expect to see ~ 0.2 events at best
3. Could be something VERY exotic (eg. H^+)
   - Will simply need more data

"Best" interpretation is that we are seeing SM top

So Is This a Top Discovery?

Statistically marginal signal

- probability of background fluctuation 0.26%
- Really would like to have $\times 2$ more data

Two consistency checks raise some concerns

1. Predicted rate of QCD W+4 jet events too large

Process	Observed Events
Predicted QCD W+4 jet rate	$8 \pm 3^{+6}_{-2}$
Estimated rate from $t\bar{t}$	$11.6^{+5.6}_{-4.5}$
Observed W+4 jet rate	9

2. Observe an apparent excess of $Z + 4$ jet events
   - Observe 3 Z° + 3 jet events and 2 Z° + 4 jet events
   - Both Z° + 4 jet events have b tags!
     - Expect 0.64 ± 0.06 background tags

Both observations are statistics-limited

- Cannot rule out statistical fluctuation
- But cannot rationalise these two observations away either

But More Data is Coming!

Tevatron began colliding in January 1994

- Run Ib will continue through end of 1995
- Maximum luminosity now 1.6×10^{31} cm^{-2}s^{-1}
- Goal is for CDF/D0 to collect ~ 150 pb^{-1}

This will allow us to confirm the "top" signal

- After ~ 20 pb^{-1} have a new $e^- \mu^+$ event
- Are working on repeating Run 1a analysis
- Hope to have preliminary results by spring 1995

Based on Run Ia results:

- Expect ~ 50 reconstructed $W + 4$ jet events
- Background of order $15 - 20$ W+4 jet events

Prospects for Run Ib

Expect statistical uncertainty on M_{top} to scale as $1/\sqrt{N}$

- Have performed MC "toy" studies to evaluate this
- Expect statistical $\sigma_M \sim 6$ GeV/c^2
- Systematic σ_M hardest to control
  - Calibrate gluon radiation using other processes
  - Sensitivity to background shape also should go as $1/\sqrt{N}$
- Reasonable to expect total systematic uncertainty to drop as $1/\sqrt{N}$

Can also hope to begin to estimate couplings

- Will have of order 10 dilepton events
- Expect of order 50 lepton + jet events
- Might expect $\sim 30\%$ measurement of

$$\frac{\text{BR(top} \rightarrow \text{leptons)}}{\text{BR(top} \rightarrow \text{hadrons)}} \tag{1}$$

Prospects for Run II

Parameters for Run II coming into focus

- Expect maximum luminosity of $1 - 2 \times 10^{32}$ cm^{-2}s^{-1}
- Total dataset of 1000 pb^{-1}
- Run from 1999 to 2003 (?)

CDF upgrades designed to handle 5×10^{31} cm^{-2}s^{-1}

- Upgraded Plug/Forward calorimeter system
- More complete SVX coverage ($\times 2$)
- New trigger and electronics
- Central tracking could be in trouble...

Run II Top Physics

Top physics would enter a new era

- Expect of order 300 fully reconstructed $t\bar{t}$ decays
- How well can we measure the mass?
  - Naive estimate is $\sigma_{stat} \sim 3$ GeV/c^2
  - Systematic uncertainty should scale similarily
  - Should realise better than $\sigma_M \sim 5$ GeV/c^2
- Uncertainties in semileptonic branching ratios should be better than 20%
  - Hard to predict without better estimate of cross section
  - But look at bottom SL BR uncertainty for reality check

$\boxed{\text{Conclusions}}$

In summary:

- CDF has observed a clear signal for top
  - 2 Dilepton events
  - 13 W+jet events with b quark tags
  - Standard Model backgrounds are $5.7^{+0.49}_{-0.44}$
- Best estimate of top quark mass is

$$M_{top} = 174 \pm 10^{+13}_{-12} \quad \text{GeV/c}^2$$

However:

- Statistical significance needs to be improved
- Theoretical W+jet rate appears too large
- Details of Z+jet production raise questions
- Only consistent with D0 data

More data is on its way to resolve these questions