Observation of Top Quark Production

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1. Review of Prior Results
2. Description of new CDF experiment
3. Results of CDF Search
4. Outlook & Conclusions

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Introduction: Why 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

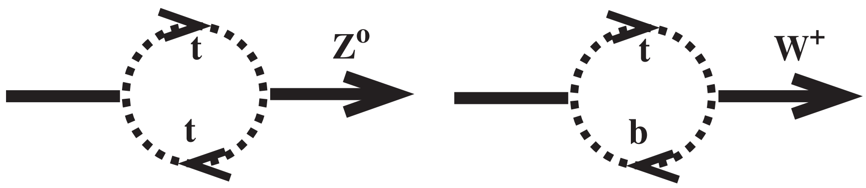
Electromagnetic force	γ
Strong force	eight gluons
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Gravity	gravitons

$\boxed{\text{SM Predictions for Top Quarks}}$

The asymmetry in $e^+e^- \rightarrow b\bar{b}$ scattering implies that b is part of SU(2) doublet

- top quark has standard SU(2) couplings
- CKM matrix predicts dominant decay $t \rightarrow W^+ b$

Corrections to $W^\pm$ and Z° masses depend on heaviest fermion



- LEP, SLD measurements on the Z resonance require

$$M_{top} = 178 \pm 10^{+18}_{-19} \text{ GeV/c}^2$$

D. Schaile, CERN-PPE/94-162

CDF Reported Evidence for Top in 1994

CDF reported observation of 2 dilepton events

- Expected ~ 0.5 events in this channel

Observed 10 lepton+jet events with b quark "tag"

- Expected 5.4 events background
- 7 events fully reconstructed

DØ had observed excess of events

- found 18 events when expected ~ 8 from background

What Does it Take to Discover Top?

- Observe "anomalous" production of W^+W^- events
  - Use dilepton events – both W's decay leptonically

- Observe W^+W^- events associated with a b quark
  - Use lepton + jet events

- Show events come from heavy fermion decays

- Confirm rate is consistent with $t\bar{t}$ production
  - Measure cross section using tagged events

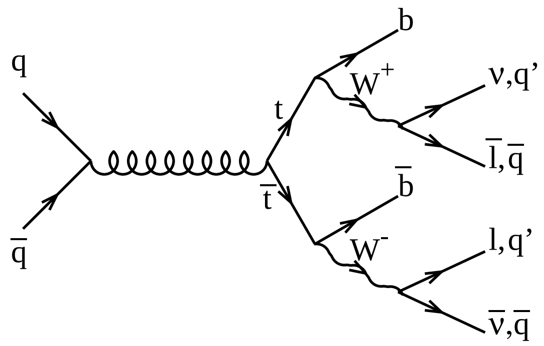
1992-95 Collider Run

CDF and DØ have collected $\times 3$ more data

- Run 1A (1992-93) provided ~ 20 pb^{-1}
- Run 1B (1994-95) has produced another ~ 55 pb^{-1}
  - DØ had updated results on top search (+22 pb^{-1})
- Will report on ~ 65 pb^{-1} of CDF data

By far the largest and most sensitive dataset to top

- For a top quark with a mass of 160 GeV/c^2
  - expect to observe 3-4 dilepton events
  - expect to observe 30 lepton + jet events



Dilepton Top Quark Search

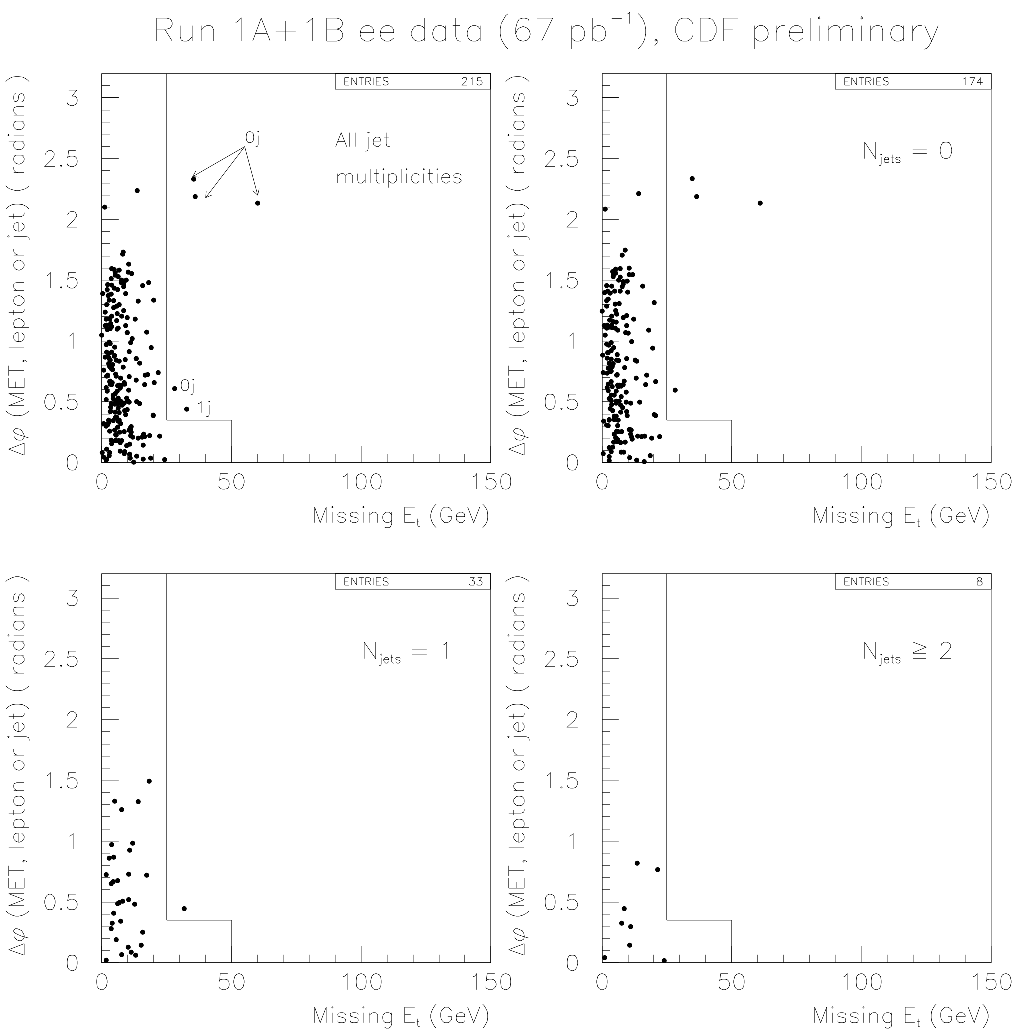
$t\bar{t}$ decaying into 2 leptons create unique signature

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

CDF performed a search requiring

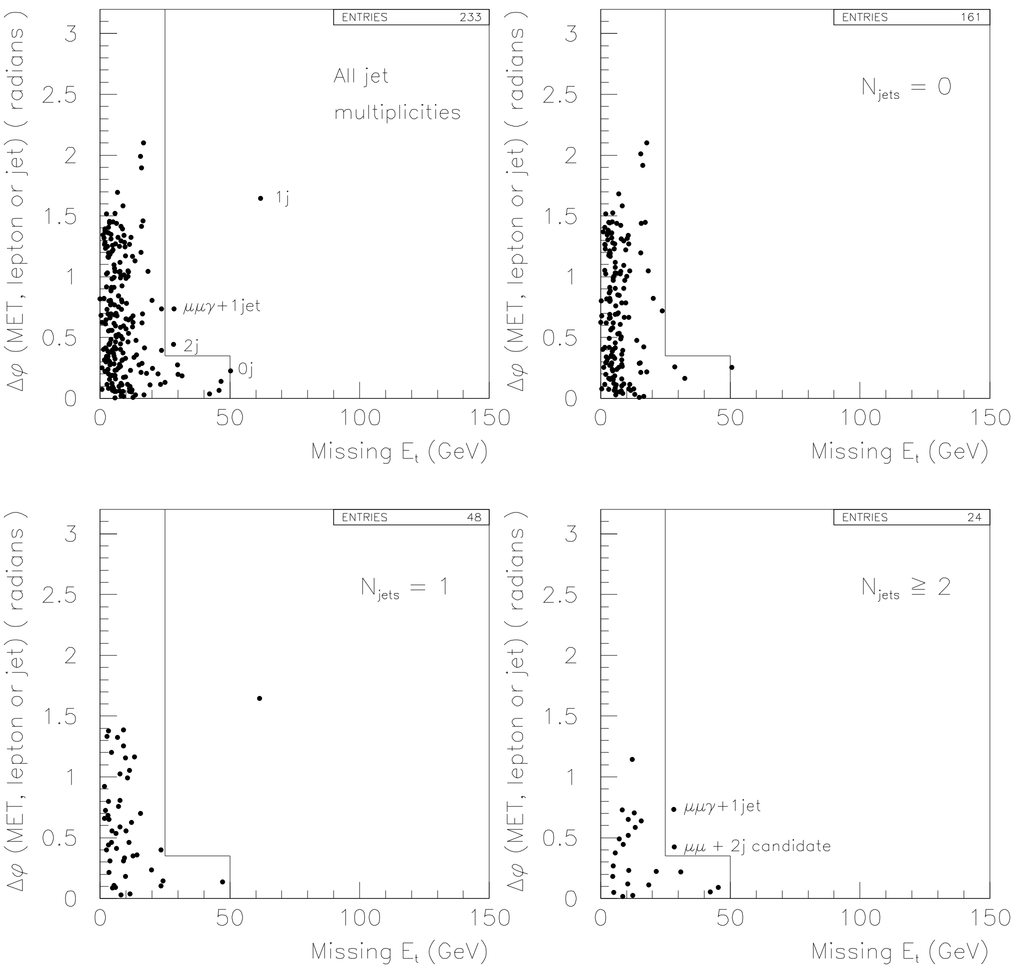
- Two clean, high P_T lepton candidates
- Missing transverse energy $\not{E}_T > 25$ GeV
- Require two jets with $E_T > 10$ GeV and $|\eta| < 2.0$
- Reject specific backgrounds (e.g. Z°)

Dielectron Data for Run 1A and 1B



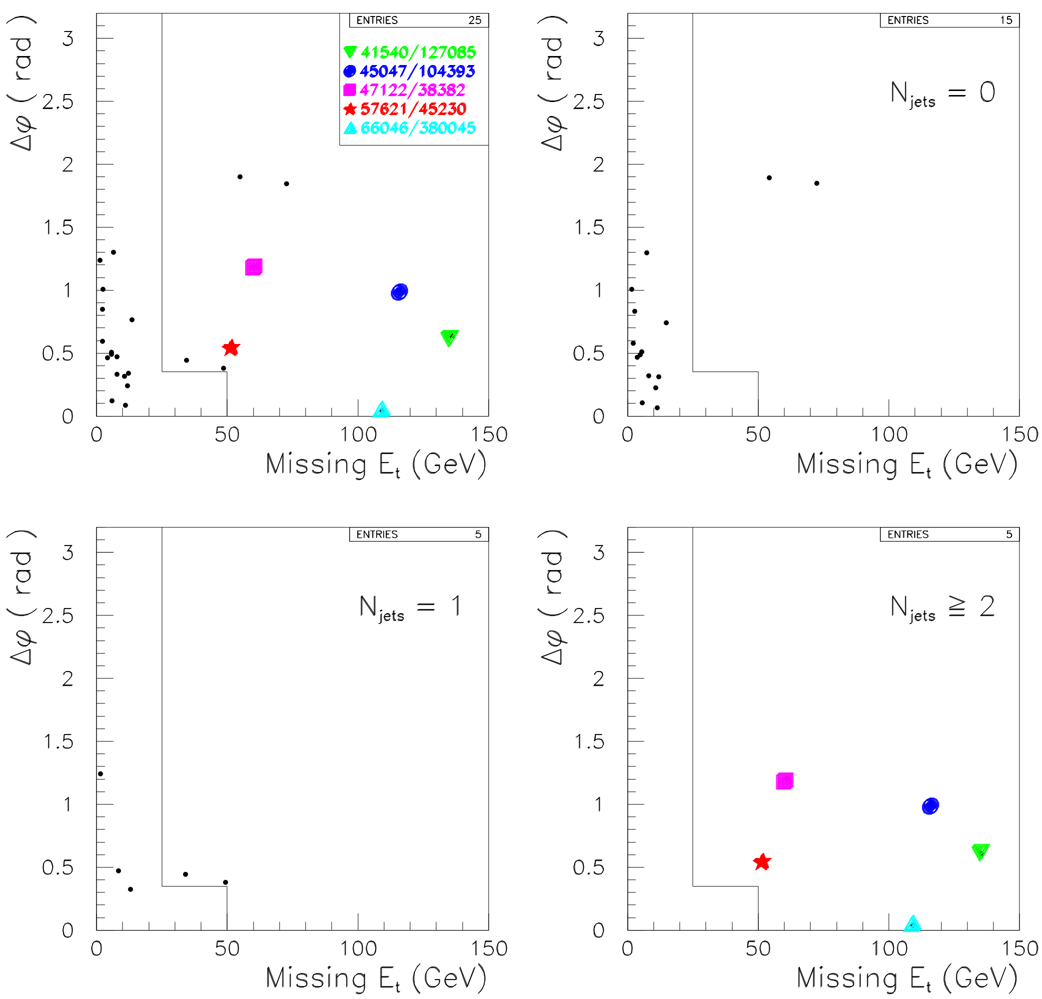
DiMuon Data for Run 1A and 1B

Run 1A+1B $\mu\mu$ data (67 pb^{-1}), CDF preliminary



Electron-Muon Data for Run 1A and 1B

$e\mu$ data: $\Delta\varphi$ (MET, lepton or jet) vs Missing E_t



Summary of Dilepton Search

Observe a total of 6 candidate events

- Observe 1 $\mu^+\mu^-$ event and 5 $e\mu$ events
- Expect 1.3 ± 0.3 events from background

Background	Expected Background Rate
$Z \to \tau^+\tau^-$	0.38 ± 0.07
One or both leptons fake	0.23 ± 0.15
$b\bar{b}$	0.03 ± 0.02
WW, WZ and ZZ	0.21 ± 0.07
Drell-Yan	0.44 ± 0.28
Total	1.3 ± 0.3

Probability of background fluctuation is 3.3×10^{-3}

Lepton + Jets Search Philosophy

Decay mode with the greatest sensitivity is “lepton+jets”

- About 30% of $t\bar{t}$ events decay this way
- Look for $W \to l\nu_l$ decay
- Require two jets from $W \to q\bar{q}$ decay
- Require at least one more jet from b quarks
  - must “tag” at least one b quark jet

Selection of W candidates straightforward

- Require high P_T isolated lepton candidate
- Require significant $\not{E}_T$
- Require three or more high P_T jets

Have now quadrupled our sample of $W+ \geq 3$ jet events

- Have 203 events before b tagging
- Expect ~ 30 to come from $t\bar{t}$ production

B Tagging Techniques

Use two properties of b quarks to identify them

1. 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 15% of $t\bar{t}$ events to have at least one SLT tag

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

   - CDF uses Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 42% of $t\bar{t}$ events to have at least one SVX tag

Idea is to just "count" number of tagged events

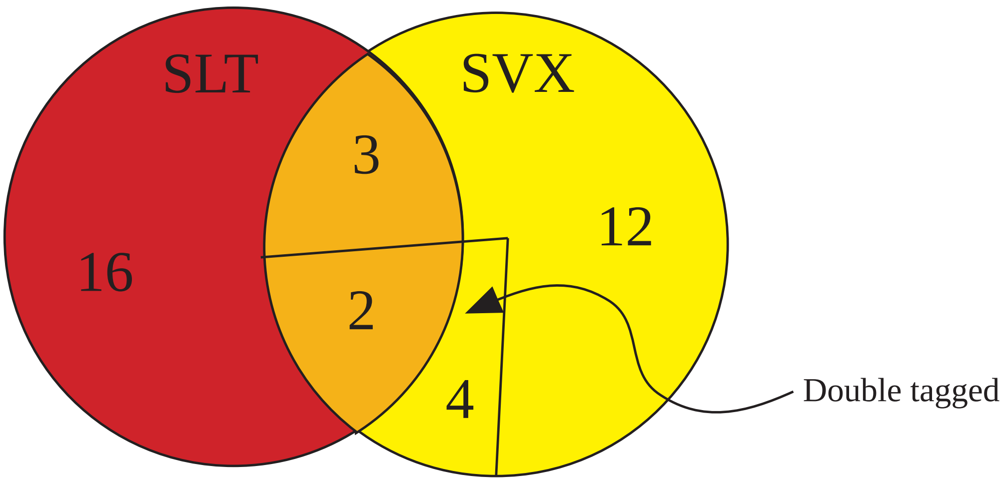
b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

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

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+1 jet	50 ± 12	40	159 ± 25	163
W+2 jet	21 ± 7	34	46 ± 7	55
W+$\geq$ 3 jet	6.7 ± 2.1	27	15.4 ± 2.3	23

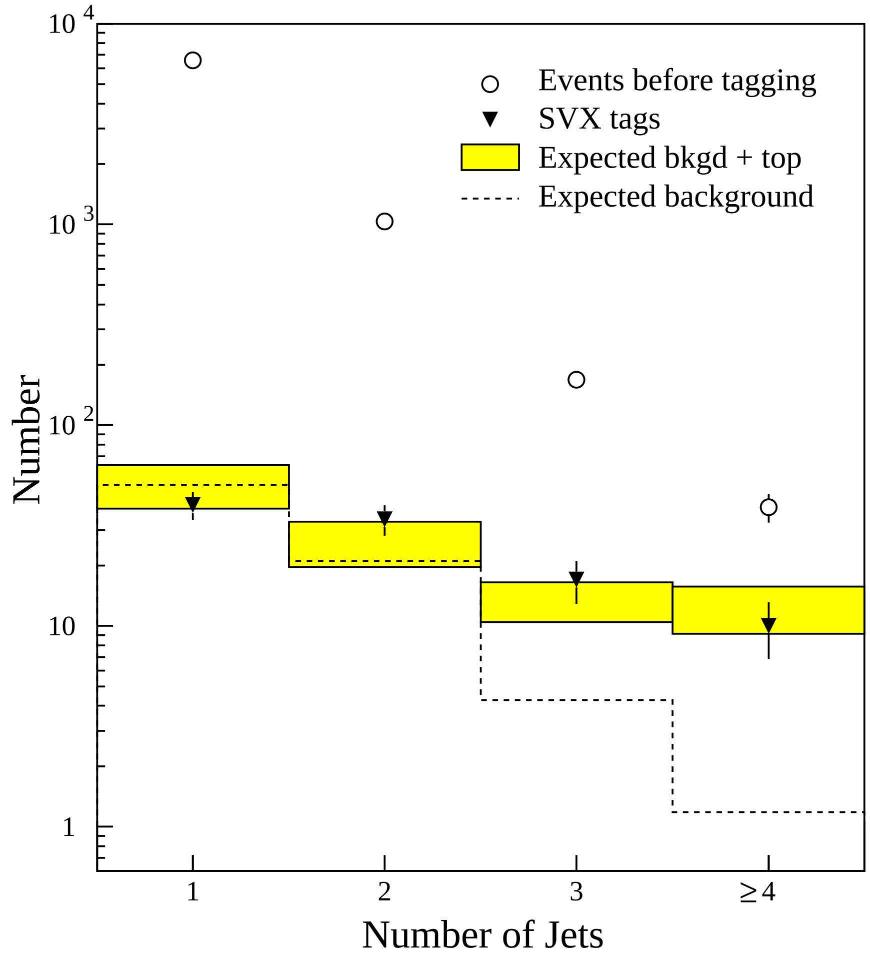
- Probability of background fluctuation is 1×10^{-6}
  - Combining SVX, SLT and DIL channels
- Agrees well with expected rate from $t\bar{t}$ production



SVX Tagging Results

The SVX tagged sample is single most significant observation

- Observe 27 tags when we expect 6.7 ± 2.1 background
- Probability of background fluctuation 2×10^{-5}



Measurement of Top Mass

We use event kinematics to estimate top quark mass

- Require events to have a fourth jet
  - Require $E_T > 8$ and $|\eta| < 2.4$ for 4rth jet
  - High efficiency ($\sim 85\%$ for $t\bar{t}$)
- Combine all possible jet pairs to form $W \to q\bar{q}$
  - Choose one with best χ^2
  - Require $\chi^2 < 10$
- Use b-tag information to identify b quark jet
- Fit events requiring kinematic constraints

This selection leaves us with 19 tagged events

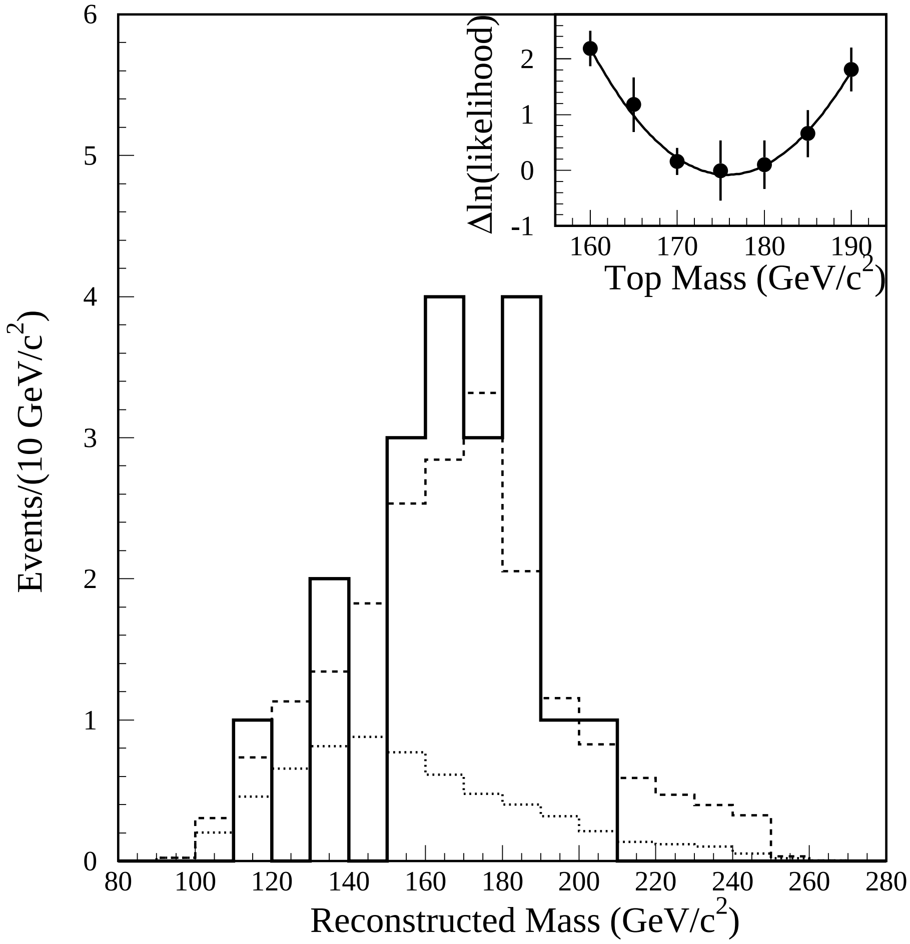
- Estimate background to be $6.9^{+2.5}_{-1.9}$ events
  - Primarily QCD W+jet

Procedure is dependent on theory predictions

Result of Mass Fits

The fitted mass for the 19 events is consistent with $t\bar{t}$

- Probability that background would fluctuate to give peak with similar significance is $< 2 \times 10^{-2}$



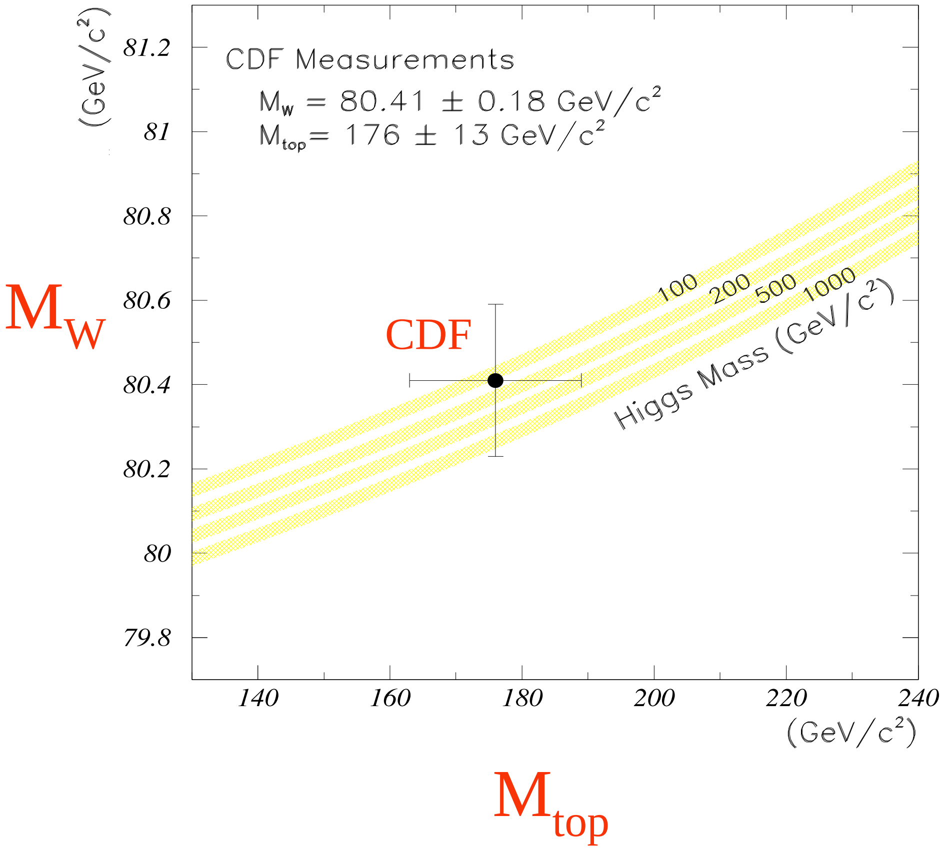
$$M_{top} = 176 \pm 8 \pm 10 \quad \mathrm{GeV/c^2}$$

Physics Comments

Most interesting immediate result is how heavy top appears to be

- In good agreement with indirect measurements

W Mass vs. Top Mass

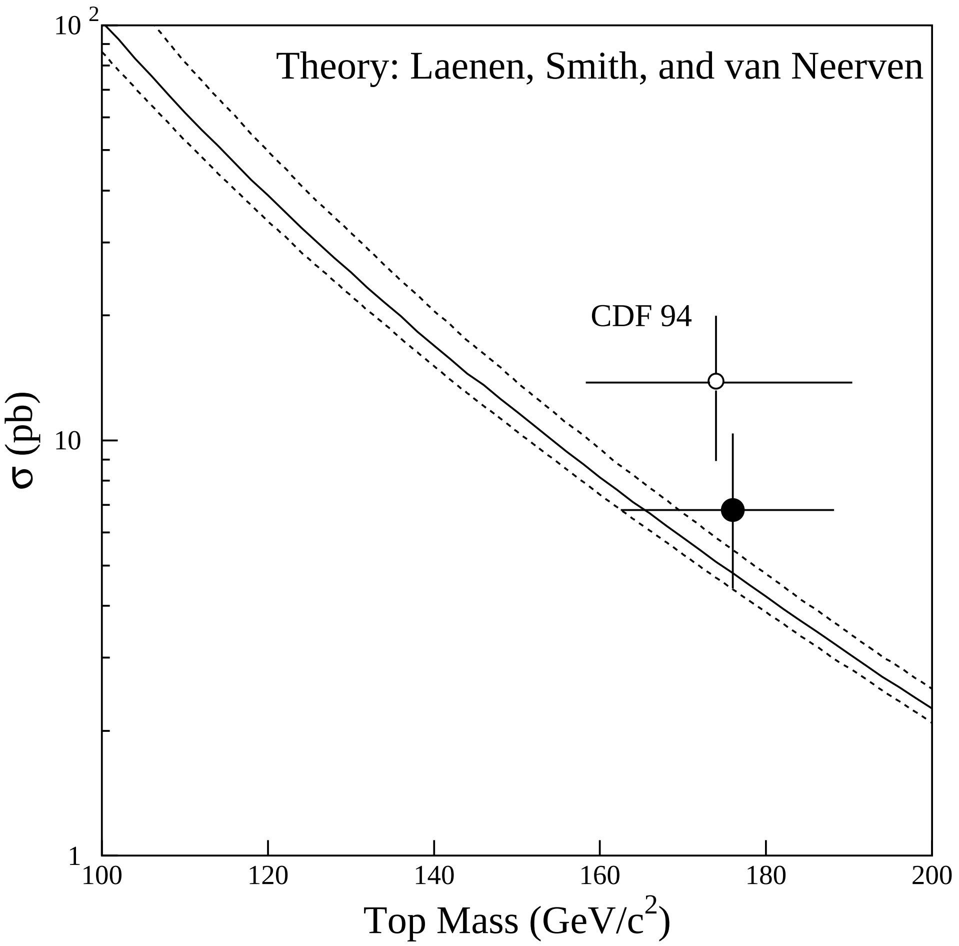


Cross Section Measurement

Use the channel with least background to estimate σ

- Subtract backgrounds from SVX-tags
  - Estimated background 5.5 ± 1.8 events
- Correct for tagging efficiency and acceptance
  - Efficiency is 0.0338 ± 0.0087

$$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4} \text{ pb}$$



Consistency Checks Revisited

Two checks last year raised concern

- Rate of $W + 3$ jet versus $W + 4$ jet events
  - Didn't see "enough" $W + 4$ jet events
- Saw two $Z + 4$ jet b-tagged events – expected 0.6

Both appear to have been statistical fluctuations

1. Predicted rate of W+4 jet events now in good agreement

Process	Observed Events
Predicted QCD W+4 jet rate	13 ± 6.5
Observed W+4 jet rate	25 ± 6

2. Have not observed more tagged $Z + 4$ jet events

Number of Jets	Observed Tags	Predicted
1 jet	15	17.5
2 jet	3	4.2
≥ 3 jets	2	1.5

Prospects for Run 1A + Run 1B

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
    - Study of $\gamma+$ jet events allow us to calibrate energy flow out of jets
  - Sensitivity to background shape also should go as $1/\sqrt{N}$
    - Will have enough statistics to measure shape of non-W background
- Reasonable to expect systematic uncertainty to drop as $1/\sqrt{N}$

Can begin to estimate couplings

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

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

Conclusions

CDF has conclusively observed top quark production

- All three channels show significant signals
- Kinematic analysis confirms interpretation
- Probability of background fluctuation:
  - Counting experiment significance 1×10^{-6}
  - Mass analysis significance $< 2 \times 10{-}2$
  - Combined significance is 3.7×10^{-7}

Best estimate of top quark mass is

$$M_{top} = 176 \pm 8 \pm 10 \quad \mathrm{GeV/c^2}$$

Result is confirmed by DØ

- Have no official details as yet

Continuing data collection for more detailed top studies