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 one high P_T lepton
- Require $\not\!\!E_T >$ 25 GeV

Problems come from physical backgrounds

- Backgrounds from "fake" leptons, etc. are manageable
- "QCD W + jet" production potentially overwhelmes top signal
- Have to find additional rejection power
  1. Place more stringent kinematical requirements
  2. Require presence of b quark jet
     - Can use semileptonic b quark decays
     - Can also use large $c\tau$ of b decays
       * This capability is unique to CDF
- Have to maintain good top efficiency

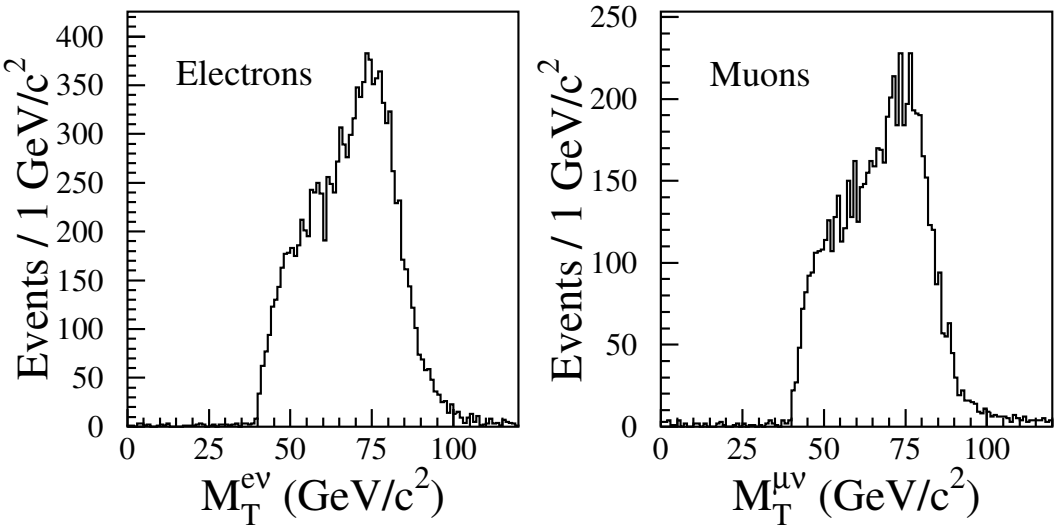
W+Jet Selection

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

Both experiments have large samples

- CDF has 11,900 $e\nu_e$ and 7,000 $\mu\nu_\mu$ candidates
- DØ has corresponding numbers



W + Jet Sample

Require $\geq$ 3 or 4 jets (from other W and b quarks)

- $E_T > 15$ GeV and $|\eta| < 2.0$
- CDF finds 52 W+$\geq$ 3 jet events
- DØ finds 24 W+$\geq$ 4 jet events

Most background sources are small:

Background	Number of Events (CDF)
Fake leptons and $b\bar{b}$	5.2 ± 2.6
WW, WZ and ZZ	2.6 ± 1.2
$Z \rightarrow \tau\tau$, 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 (CDF)
120	39 ± 6
140	22 ± 3
160	12 ± 2
180	6.6 ± 0.7
W+jets	50^{+16}_{-8}

Event Kinematics

Can use kinematic features to separate top from QCD background

- $t\bar{t}$ events are more spherical (acoplanarity)

$$M_{ij} = \sum_{\text{jets}} \frac{p_i p_j}{p^2}$$

$A = \frac{3}{2} Q_1$ where Q_1 is smallest eigenvalue of M

- $t\bar{t}$ events have more energetic partons (H_T)

$$H_T = \sum_{\text{jets}} E_T$$

DØ has applied both techniques to W+$\geq$ 4 jets

- Require $A > 0.05$ and $H_T > 140$ GeV
- Estimate W+jet background by scaling jet multiplicities
- Observe 8 events and expect 3.9 ± 1.6 from background

More on Event Kinematics

CDF uses a somewhat different approach

- Use expected distribution of jets
  - Jet 2 and 3 provide good signal-background separation
  - Form relative likelihood

$$\log(L_{\text{rel}}) \equiv \log\left(\frac{L_{\text{top}}(E_T^2, E_T^3)}{L_{\text{QCD}}(E_T^2, E_T^3)}\right)$$

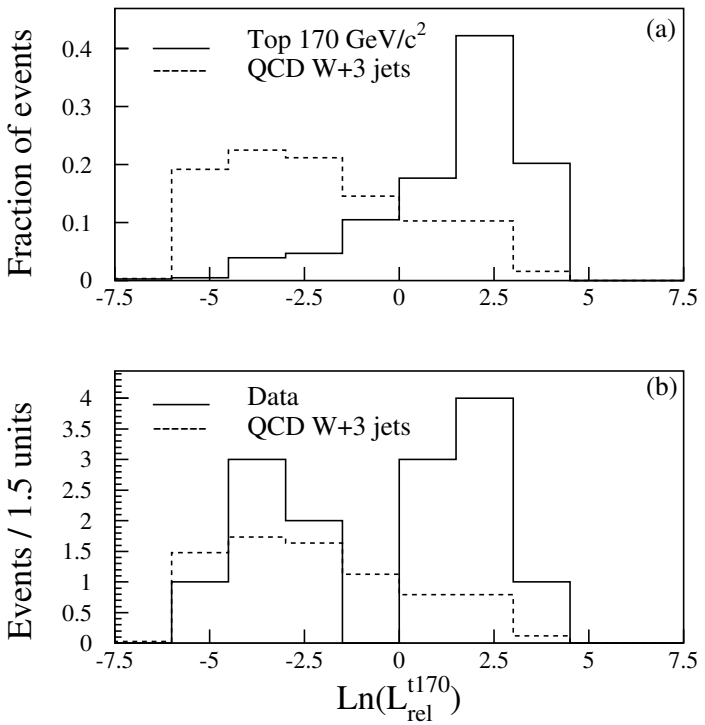
- Compute using VECBOS (QCD) and Pythia ($t\bar{t}$) MC

This technique becomes MC dependent

- Have to study effect of systematics on L_{rel}
- Calibrate technique on control samples
  - "background-enriched" W+jet sample
  - W+2 jet sample where little top is expected

Results of Event Structure Analysis

Analysis indicates that W + $\geq$ 3 jet data is mixture of top + background



- Probability that this is a background fluctuation?
  - Ask how often background would
    - give at least 8 events with $\log(L_{\mathrm{rel}}) > 0$
    - when observe 14 total
- Result is 0.8%

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)
   - CDF expects about 15% of $t\bar{t}$ events to have at least one SLT tag
   - DØ only uses soft muons
     - has higher efficiency for "cascade" decays

$$b \to cX \to \mu \nu_\mu X'$$

     - Expects to be able to tag about 20% of $t\bar{t}$ events

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 24% of $t\bar{t}$ events to have at least one SVX tag

Idea is to just "count" number of tagged events

Soft Lepton Tagging

CDF identifyies 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

DØ searches for muons with $P_T > 4$ GeV/c

- Lepton threshold does not effect acceptance significantly

CDF has studied SLT tagging using

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

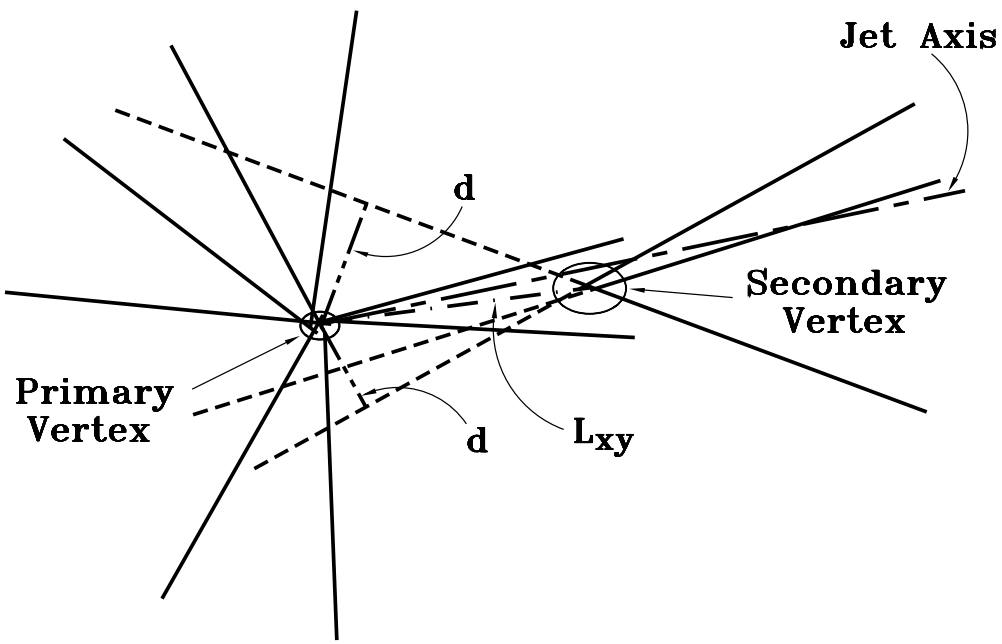
CDF efficiency and fake rate

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

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

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

CDF observes 13 tags in 10 events

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

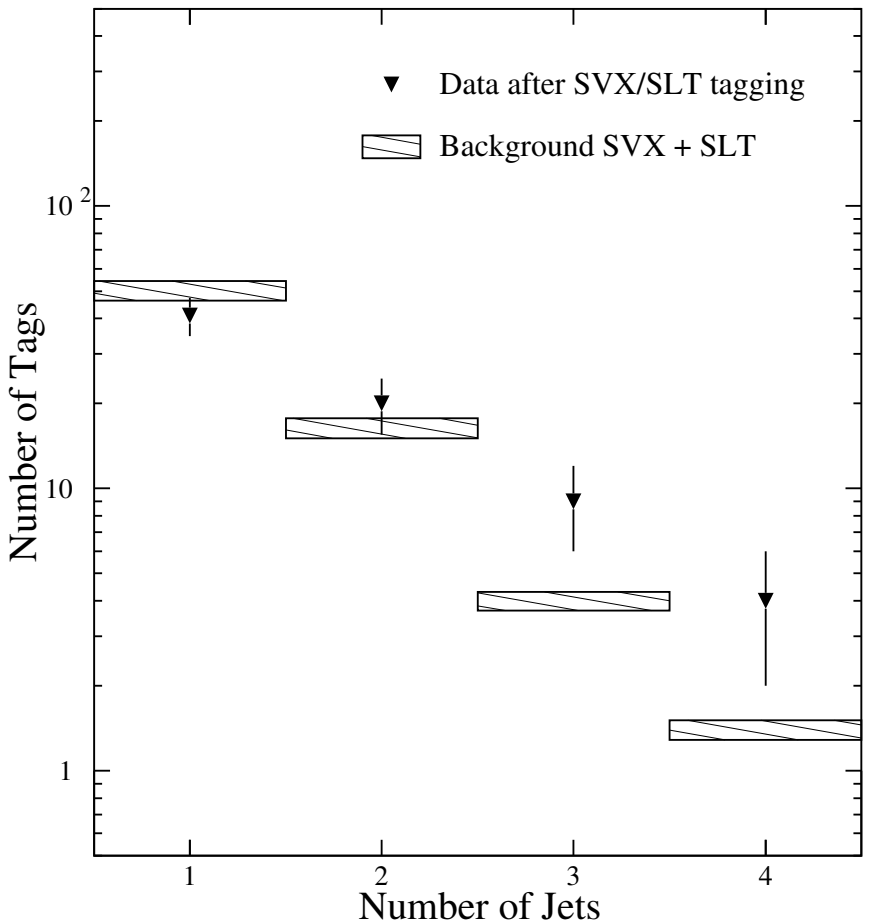
DØ observes 8 tagged events

- Expect 2.3 ± 0.4— background events
- Expect about 3 events if $M_{top}\sim$ 160 GeV/c^2

CDF 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



DØ Counting Experiment

DØ combines dilepton, kinematic and μ-tagged events

- Observe 8 μ-tagged events on background of 2.3 ± 0.4
- Observe 8 events on background of 3.9 ± 1.6 from $A - H_T$
- 2 dilepton events (expect 2.0 ± 0.2 background)

Gives a total of 18 events on background of 8.2 ± 1.7

- Probability of background fluctuation is 0.7%
- Not yet significant enough on its own

Expectations from top are

M_{top} (GeV/c^2)	Number of Events (DØ)
140	18.0 ± 2.0
160	11.8 ± 1.7
180	6.8 ± 1.0
200	4.0 ± 0.6

Features of CDF 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 $t\bar{t}$

Number of "double-tags" larger than expected from $t\bar{t}$

- Have number of tagged-events fluctuated low?
- Number of double-tags fluctuated high?

Statistical Significance of CDF Sample

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

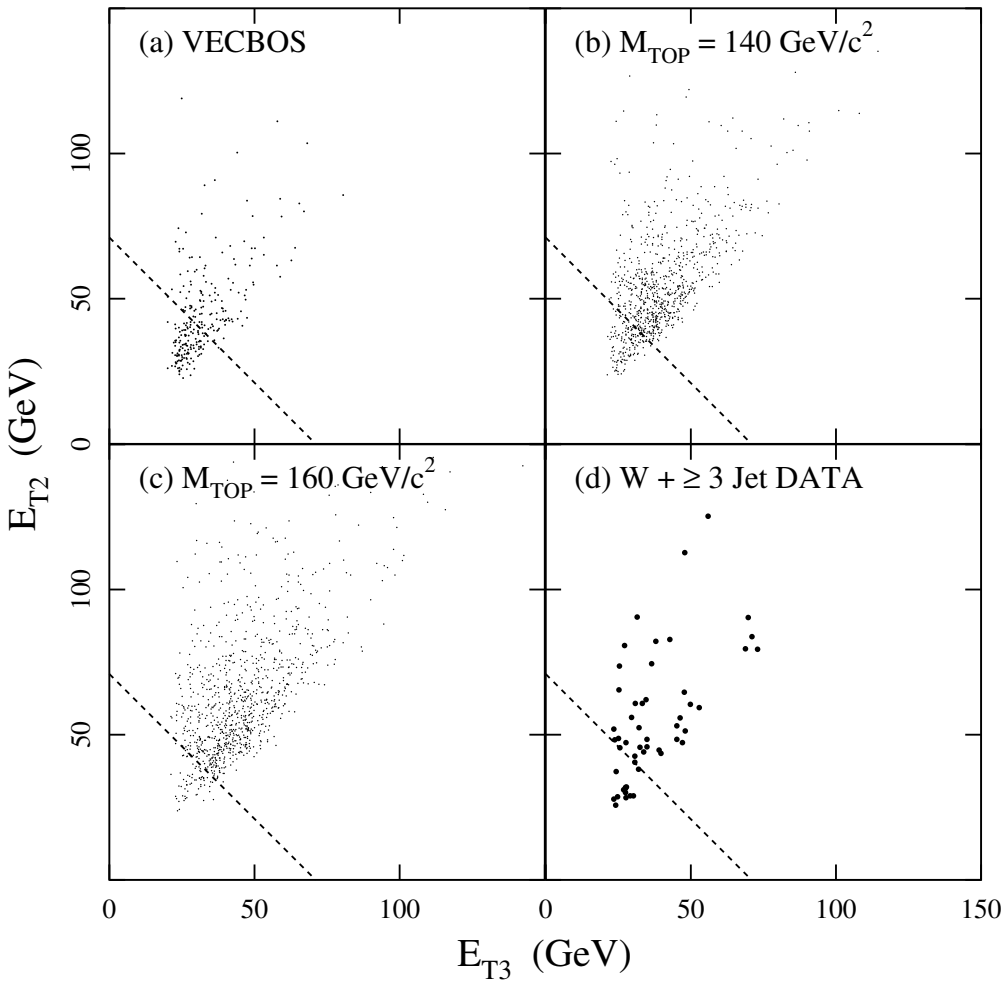
- Estimate the number of tags from the background sources
- Simulate our experiment assuming no top
- Count how often we would see at least the number of tags

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

Kinematic Features of Events

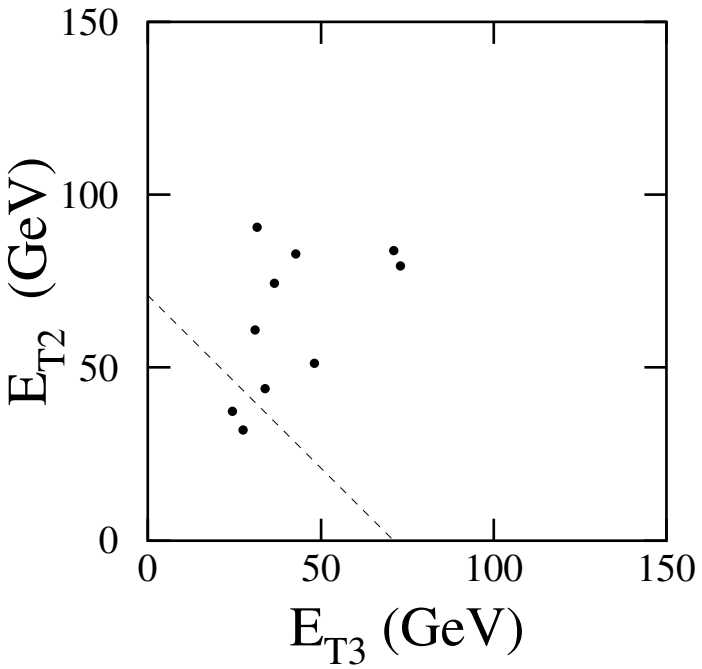
Examined the kinematics of these events

- 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

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



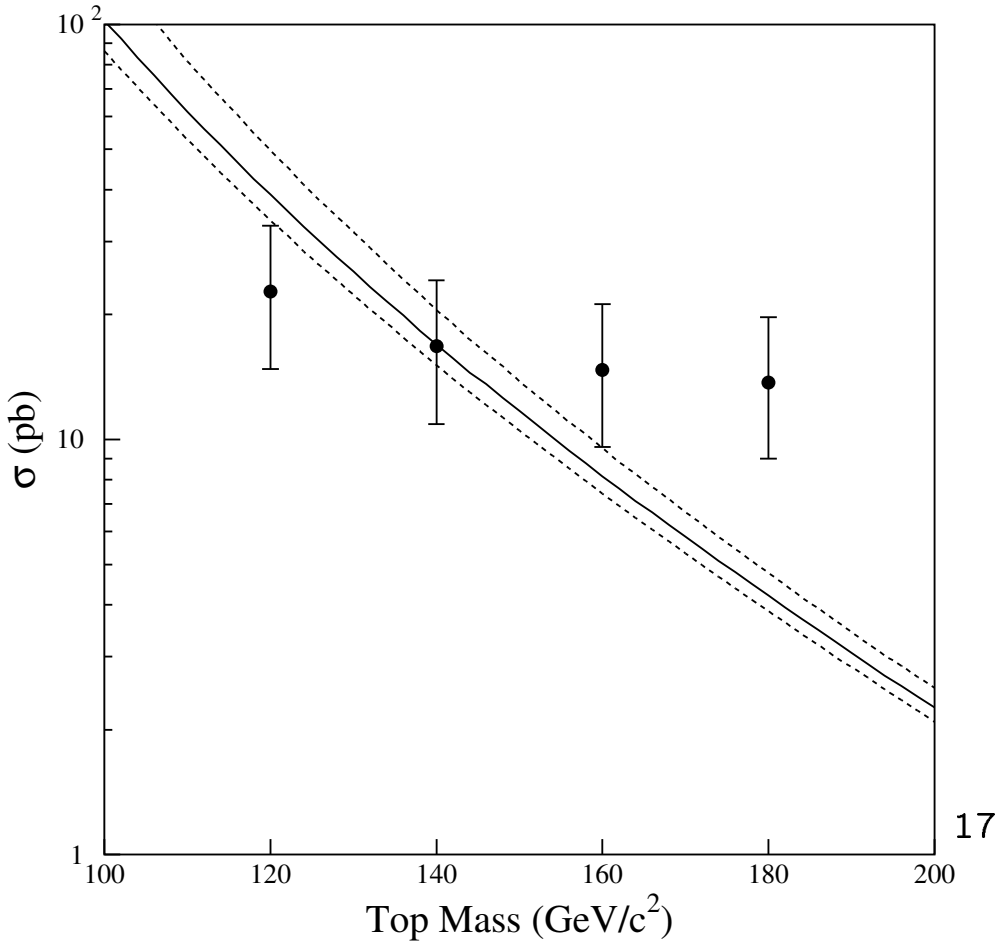
The event-structure analysis provides quanitative confirmation

- Best described as combination of $t\bar{t}$ and QCD

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 $\sigma_{t\bar{t}}$
  - Note that counting tags gives the largest possible σ
  - Reanalysis of data counting events reduces it by about one standard deviation



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

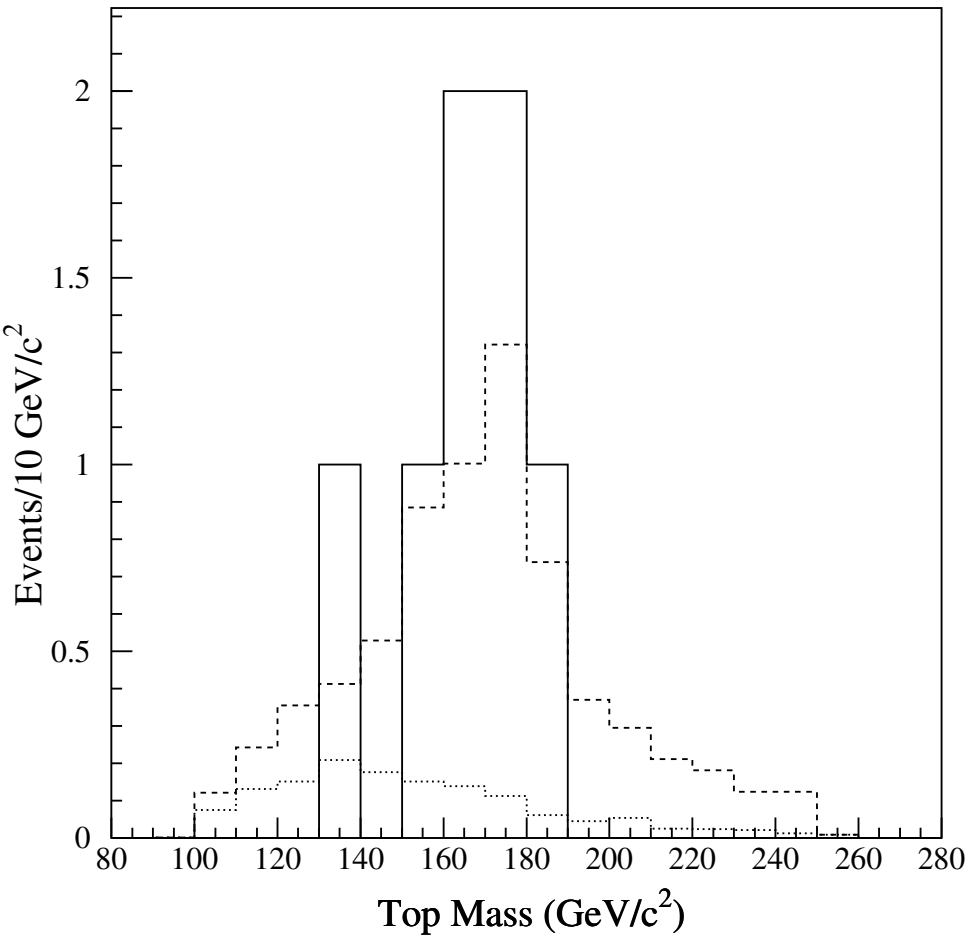
This selection leaves us with 7 tagged events

- 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 $t\,\overline{t}$

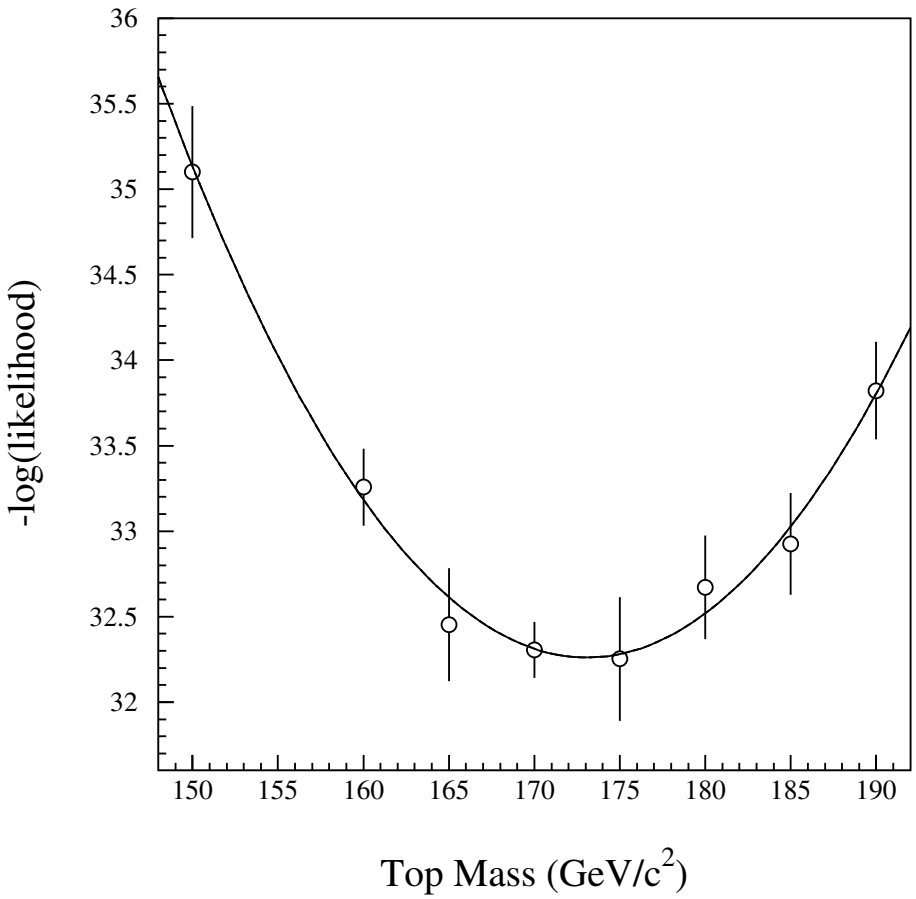


Fit the mass distribution to obtain

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

Systematic error is dominated by uncertainties in

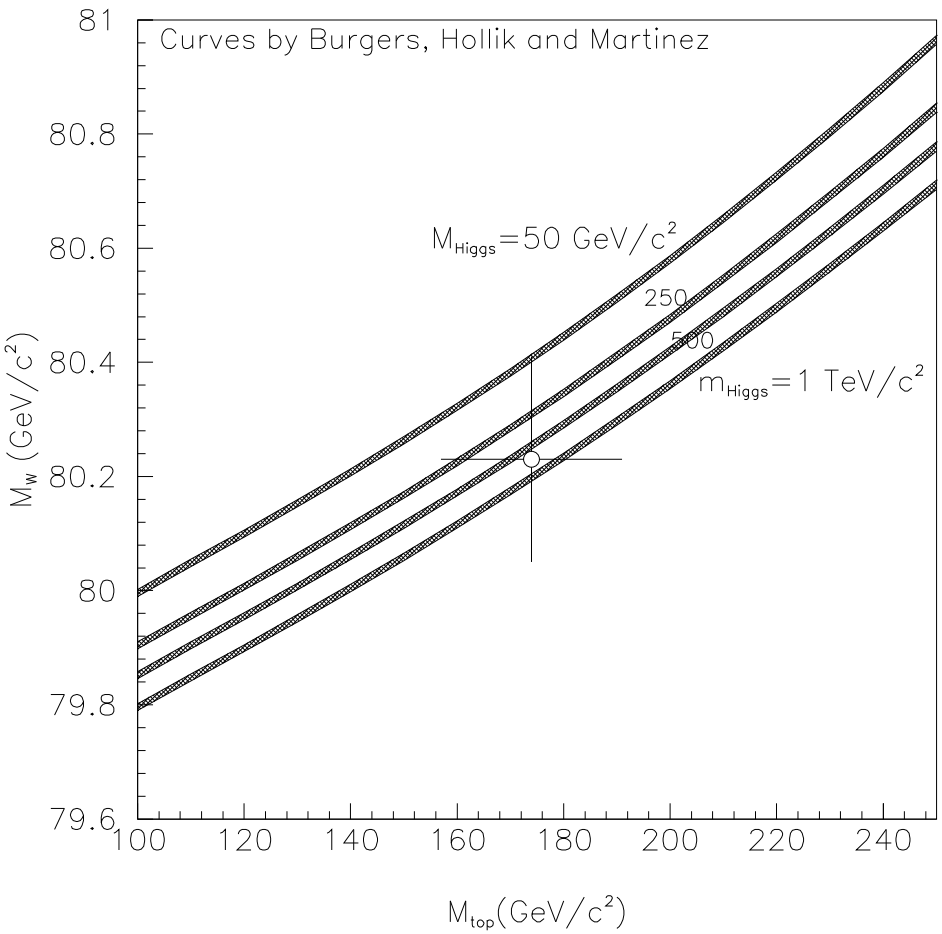
- Gluon radiation in $t\bar{t}$ production (4.4 GeV/c^2)
- Different background shapes ($\sim$ 5 GeV/c^2)
  - Not clear what shape the non-W background has



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
- Cross section is somewhat high



Other Possible 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

Now the Fine Print....

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

Future Prospects

Tevatron began running again in January 1994

- Run IB will continue through end of 1995
- Maximum luminosity of 1.7×10^{31} cm^{-2}s^{-1} attained
- Goal is for CDF/DØ to collect > 100 pb^{-1}

This will allow us to confirm the "top" signal

- Both CDF and DØ will be giving updates soon
  - CDF now has data sample of ~ 65 pb^{-1}
  - Working to repeat and extend Run 1A analysis

CDF has made many improvements to analysis

- New rad-hard SVX detector and improvements in tracking
  - Gives $\times 1.3$ in SVX tagging efficiency
- Enhanced SVX tagging algorithm (SECVTX)
  - Factor of 1.25 improvement

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

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

Prospects for Run II

Parameters for Run II coming into focus

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

DØ and CDF upgrades well along for Run II

- For CDF,
  - Upgraded Plug/Forward calorimeter system
  - More complete SVX coverage ($\times 2$)
  - New trigger and electronics
  - New central tracker...

- For DØ,
  - Solenoid and new central tracker
  - SVX detector (at last!)
  - New electronics, trigger and DAQ system

- Overall upgrade project of order \$100 M

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

Conclusions

CDF and DØ see signals consistent with top

- Most channels show an excess over background
- CDF kinematic analyses provide additional confirmation
- But still at best only $\sim 3\sigma$ effect
- Probability of background fluctuation:
  - CDF counting experiment significance 0.25%
  - DØ counting experiment significance 0.7%
  - CDF event-structure analysis 0.8%

Best estimate of top quark mass is

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

However:

- Need one experiment that gives $\geq 5\sigma$ effect
- Published CDF results have some contraindications
  - Theoretical W+jet rate appears too large
  - Details of Z+jet production raise questions

Stayed tuned as more results will be coming shortly