Searching for Top

Top can be pair-produced in matter-antimatter collisions

- It's heavy $\Rightarrow$ need high collision energies
- Look large number of collisions

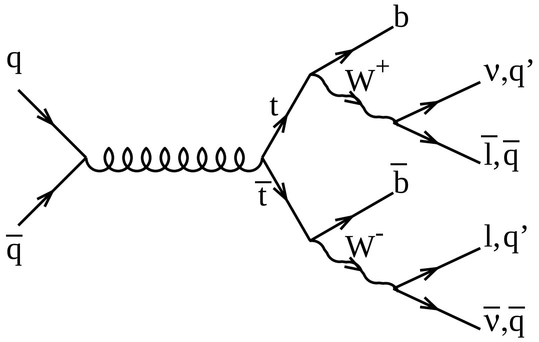
$p\bar{p}$ Collider at Fermilab is the "only" choice

- High luminosities ($\mathcal{L} \sim 5 \times 10^{30}$ cm^{-2}s^{-1})
- Highest energies ($\sqrt{s} = 1800$ GeV)

Top Quark Signatures

SM top quarks can only decay via the weak force

$$t \rightarrow W^+ b$$
$$\hookrightarrow u\bar{d} \text{ or } c\bar{s}$$
$$\hookrightarrow e^+\nu_e \text{ or } \mu^+\nu_\mu \text{ or } \tau^+\nu_\tau$$



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 2000 ton detector

Collaboration consists of

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

The Canadian IPP Group consists of

	McGill University	**University of Toronto**
Faculty	Ken Ragan	Pekka Sinervo
RA	Kurt Biery Klaus Strahl	Andreas Hölscher
Grad Students	Yunling Ye Kostas Kordas	George Sganos Andreas Warburton Hyunsoo Kim Wendy Taylor

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}
- Working on analysis of full dataset since June 1993

Most sensitive dataset acquired to date

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

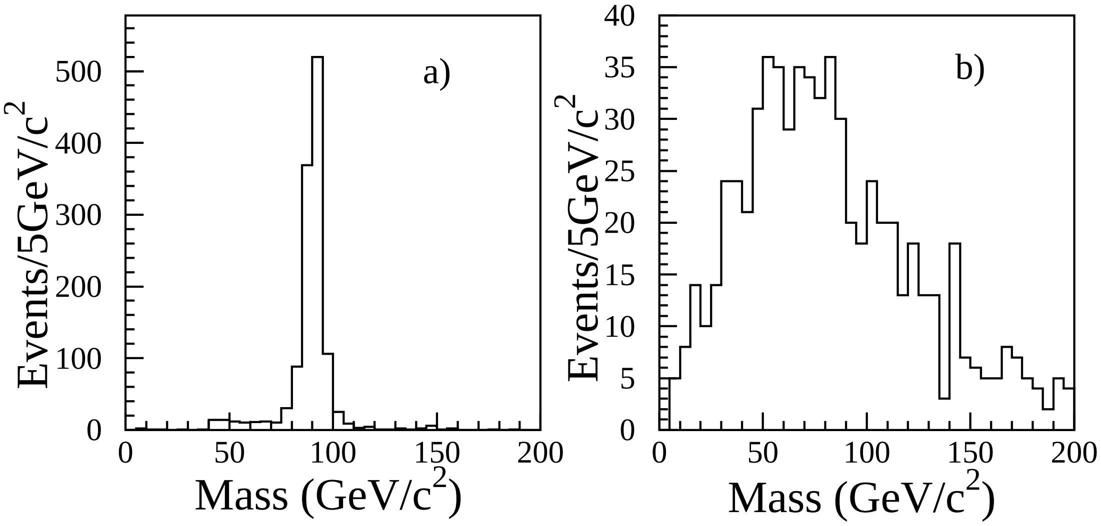
Dilepton Top Quark Search

$t\bar{t}$ 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

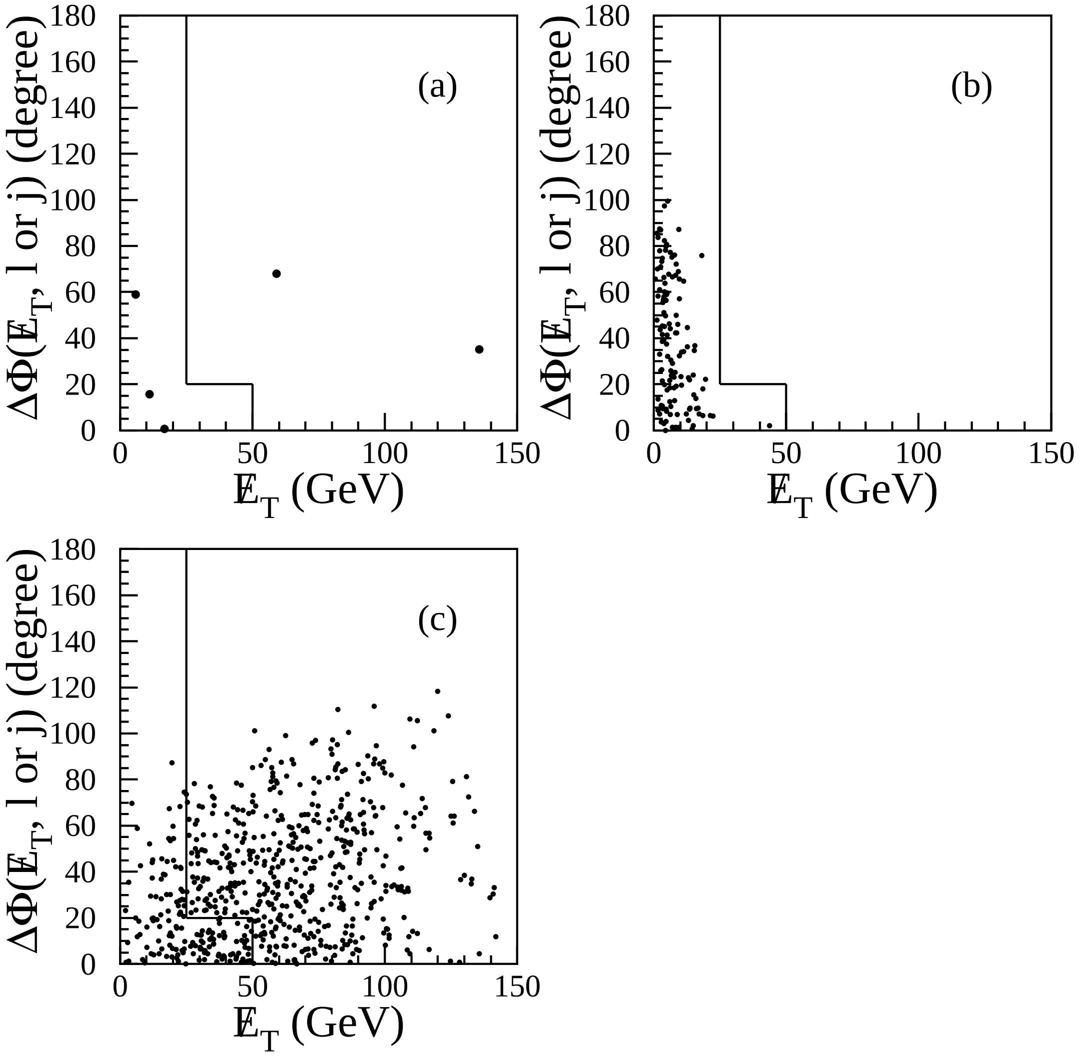
Performed a search requiring

- 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

On the other hand, we expect from top production

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

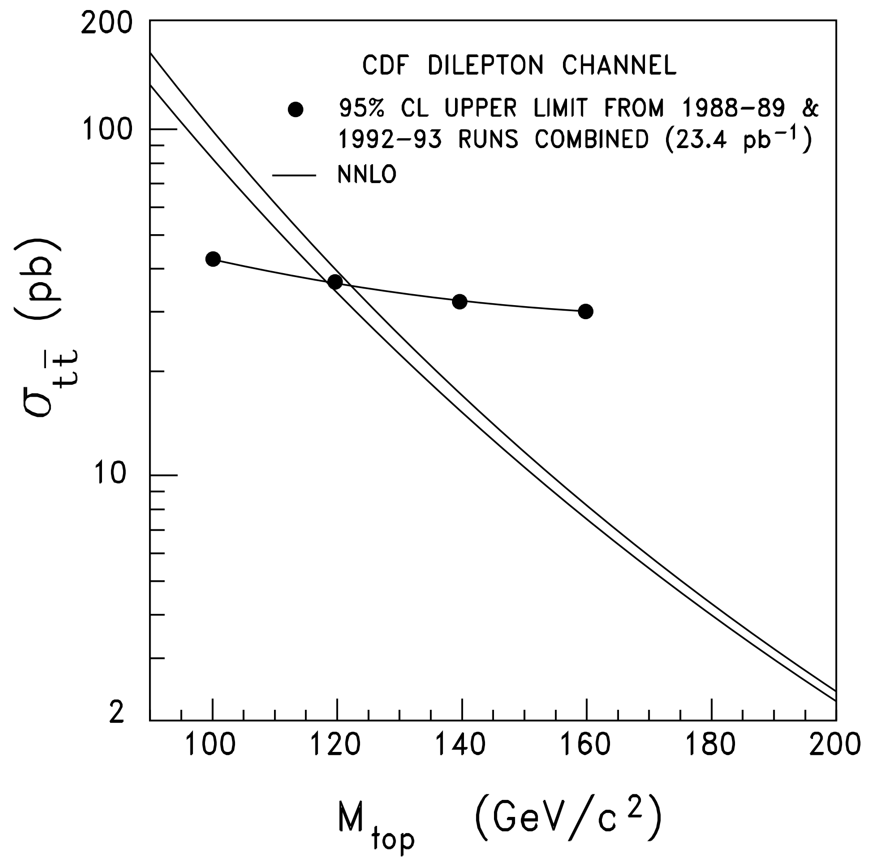
Probability 0.56 events fluctuates to ≥ 2 events is 12%

$\Rightarrow$ On its own, not statistically significant

Mass Limit from Dilepton Data

Can use dilepton data to exclude low mass top

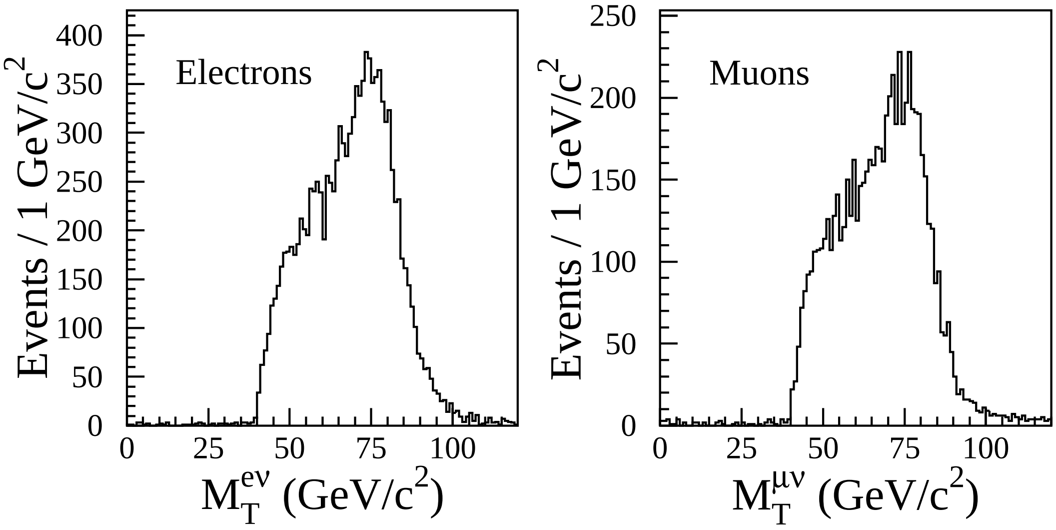
- In this case, remove jet requirement
  - Jet efficiency less certain for $M_{top} \sim 100 - 120$ GeV/c^2
  - No additional events are added to sample
- Add 3.7 pb^{-1} from 1988-89 data run (no events)
- Backgrounds increase to 3.0 ± 0.6 events
- Assume 2 events are top and set limit on σ_{top}



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



- Require 3 or more jets (from other W decay and b quarks)
  - $E_T > 15$ GeV and $|\eta| < 2.0$
  - Find 52 events with these criteria

W + Jet Sample

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
$Z \rightarrow \tau\tau$	1.7 ± 0.5
$Z \rightarrow \mu\mu$	1.5 ± 0.4
$Z \rightarrow ee$	1.2 ± 0.6
Total	12.2 ± 3.1

Would expect from $t\bar{t}$ and QCD W+jets

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}

The W+jets remain single largest background

- Reject this by searching for b quark tag

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

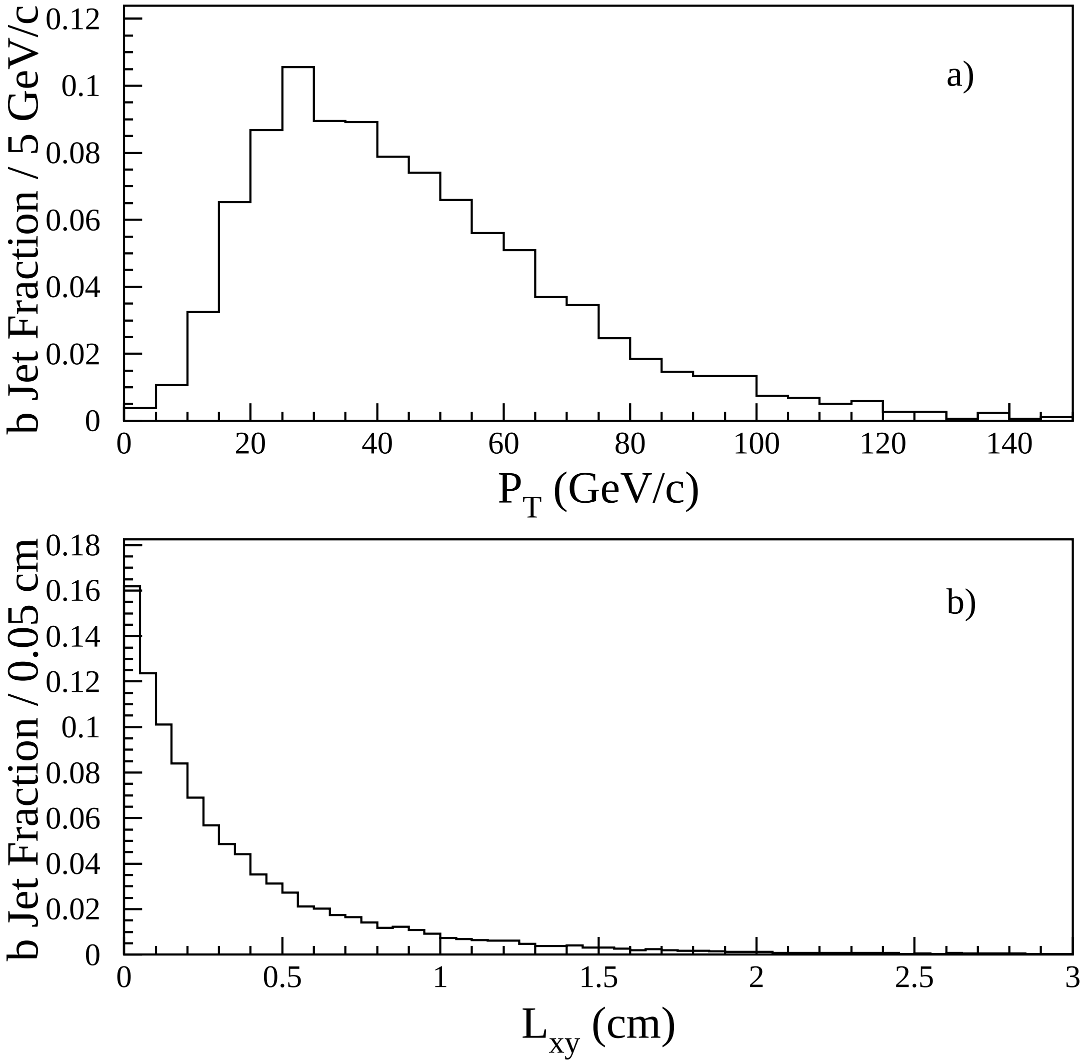
2. About 20% of b's decay via

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

   - 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

A heavy top would produce fairly energetic b quarks

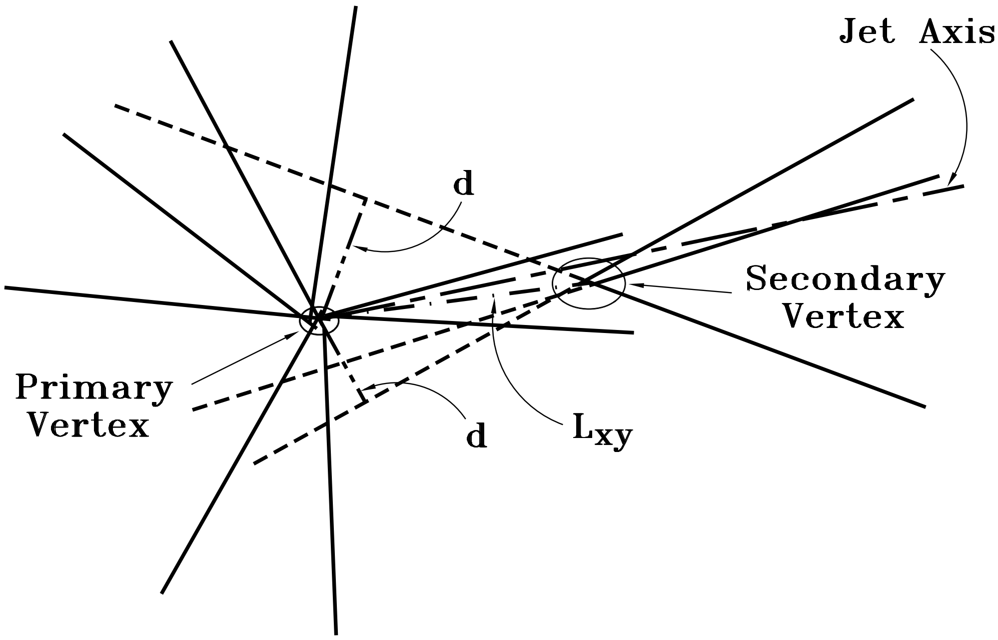
- MC predictions for $M_{top} = 160$ GeV/c^2



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



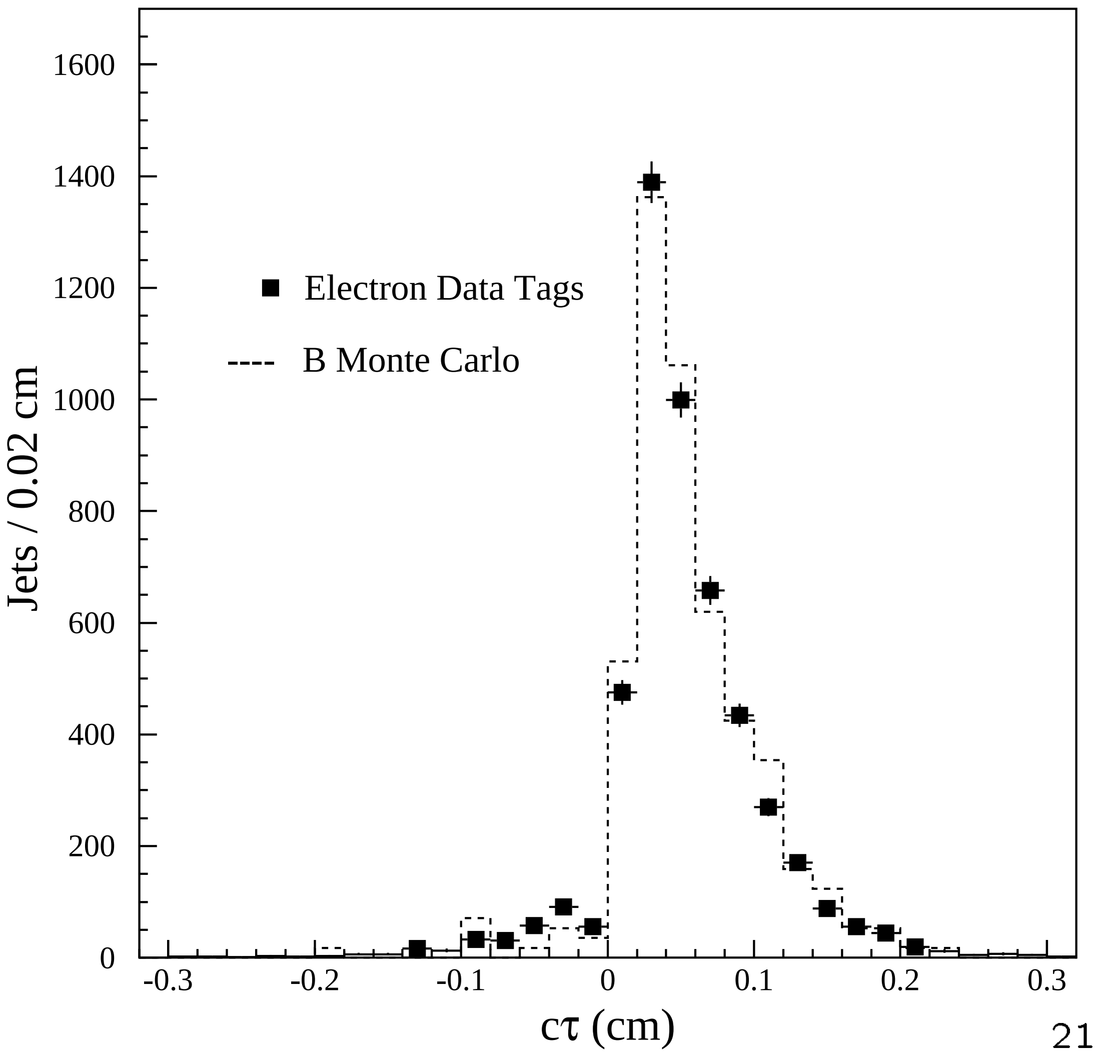
Used control samples to measure the tagging efficiency and fake rate

- 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

Inclusive electrons

Have independently estimated 37±8% of sample comes from B decays

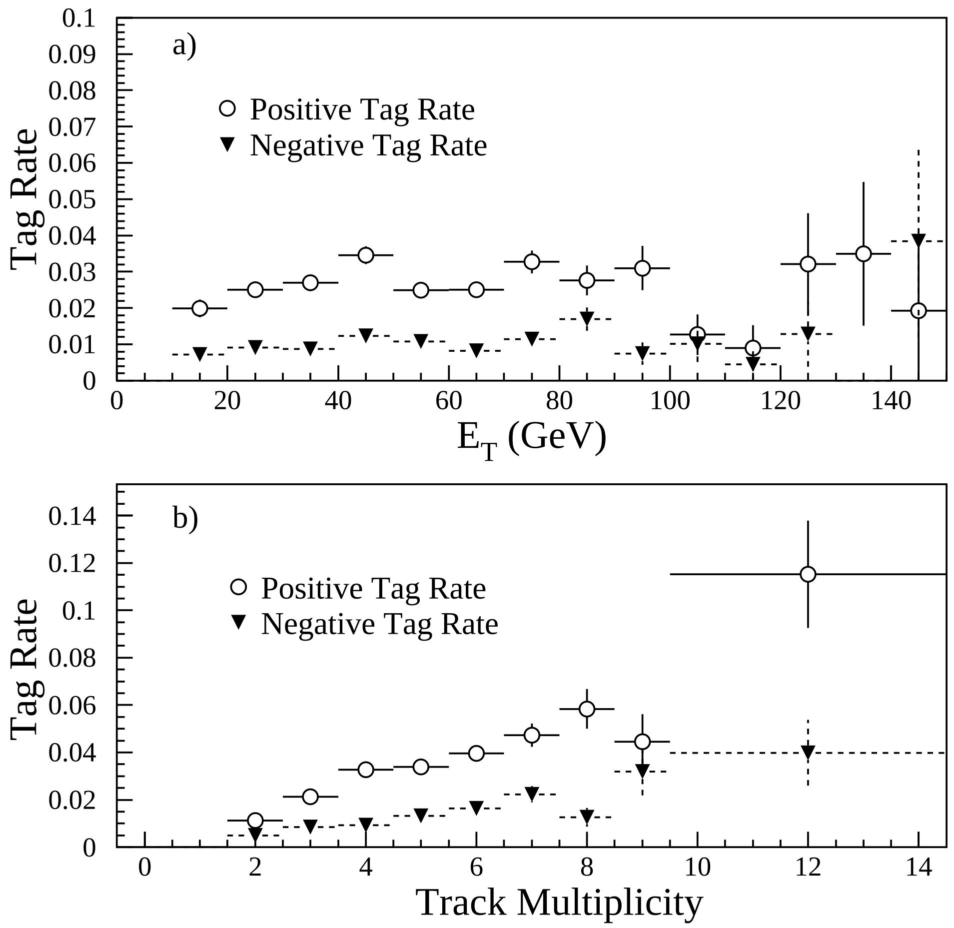
- Have measured the rate of single tags and double tags
- Compared $+ve$ pathlength tags with $-ve$ pathlength decays



SVX Tag Backgrounds

The SVX tags found in “generic” jets are due to both real heavy flavour and “mistags”

- The $-ve$ tags come only from “fake” tags
- The $+ve$ tags come from both real c and b quarks and fakes
  - Use $+ve$ rate to estimate backgrounds to tagged b quarks
  - results in an overestimate of the background



Other SVX Tagging Algorithms

Independently developed two different SVX algorithms

- Looked at $d - \phi$ correlation between tracks
  - Tracks from secondary vertex are linearly correlated
  - Search for at least three tracks with this pattern

- Converted impact parameter of track into probability of coming from primary vertex
  - Calculate probability that all tracks in jet come from primary vertex
  - Tag jets with low probability ($< 1\%$)

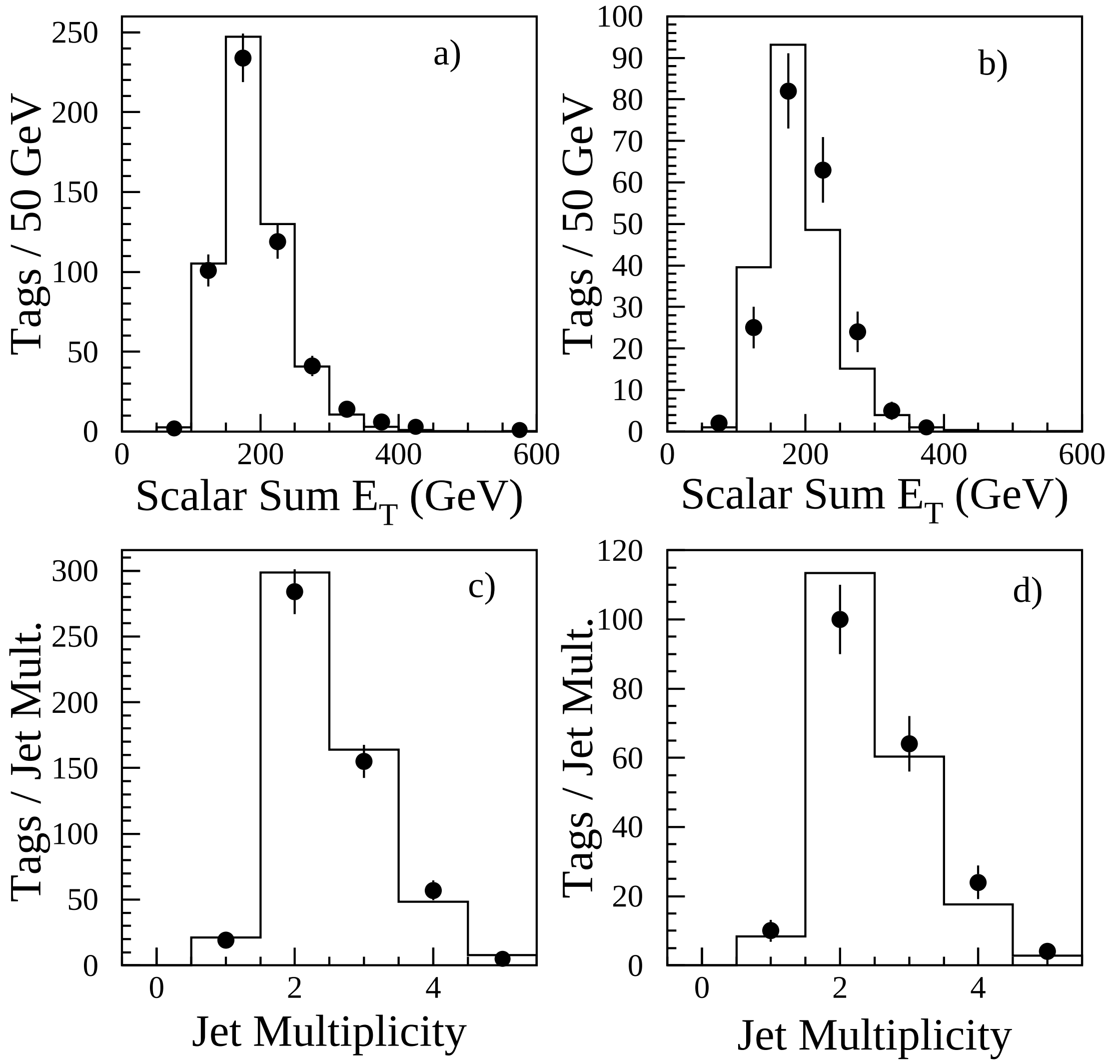
Both techniques give similar efficiencies and fake rates

- Chose JETVTX algorithm as it is best understood
- Backgrounds mostly due to real $W + b\bar{b}$ and $W + c\bar{c}$

Tagging Background Estimates

Use fake rates to estimate backgrounds in control samples

- Compare predicted and observed SVX rates in "generic" jet sample



Soft Lepton Tagging

Have good efficiency for identifying 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

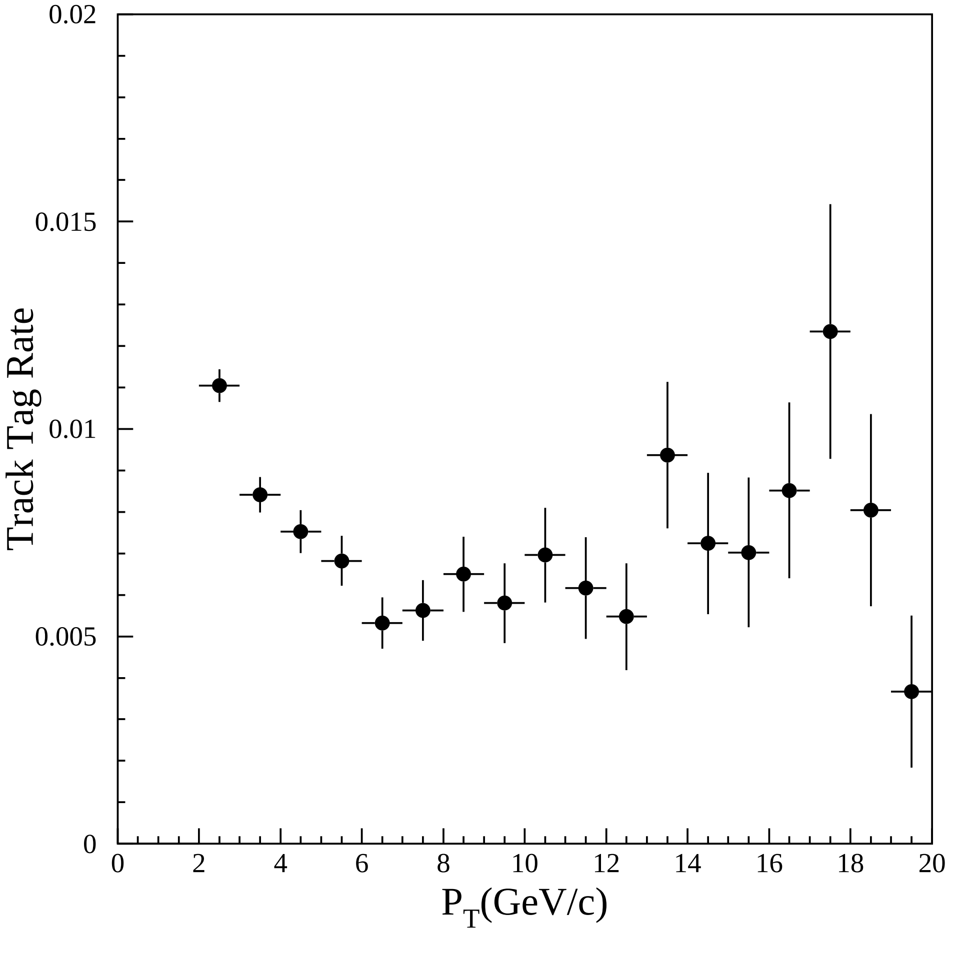
Measured efficiency and fake rates

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

Have estimated the "fake" rates using various control samples

- Generic jets
- Photon + jet and Z° + jet data samples

Fake rates for muons are largest, but still manageable

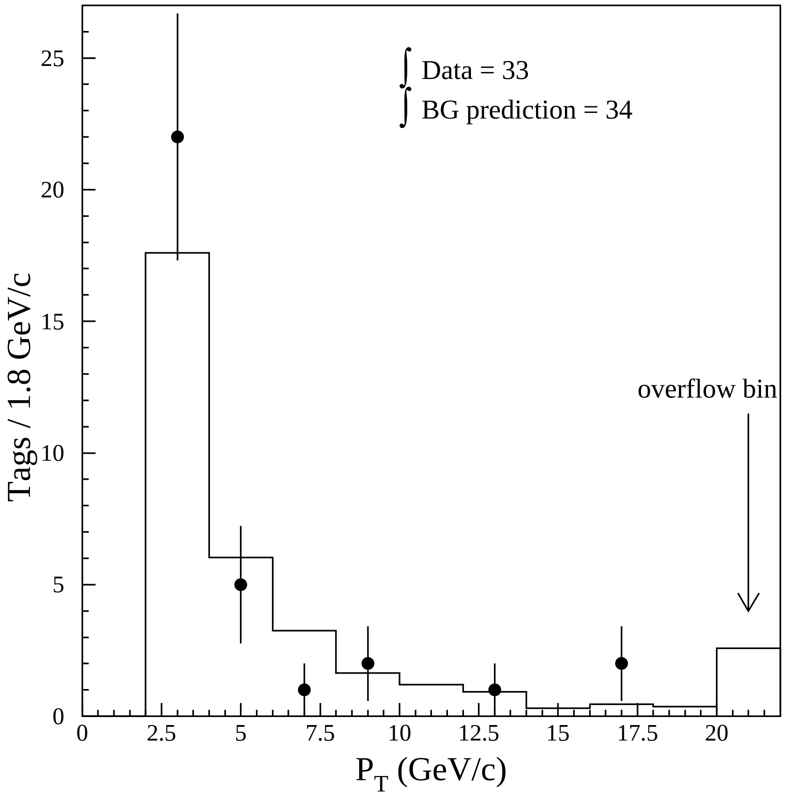


b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

- Can used fake SVX and SLT tagging rates to estimate backgrounds assuming sample has no b quark content
- 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



Alternative Background Calculation

SVX tag background dominated by “physical” sources

- Background is conservatively overestimated
- Measure fake rate independently using $-ve$ decay lengths
- Predict physical backgrounds using theory

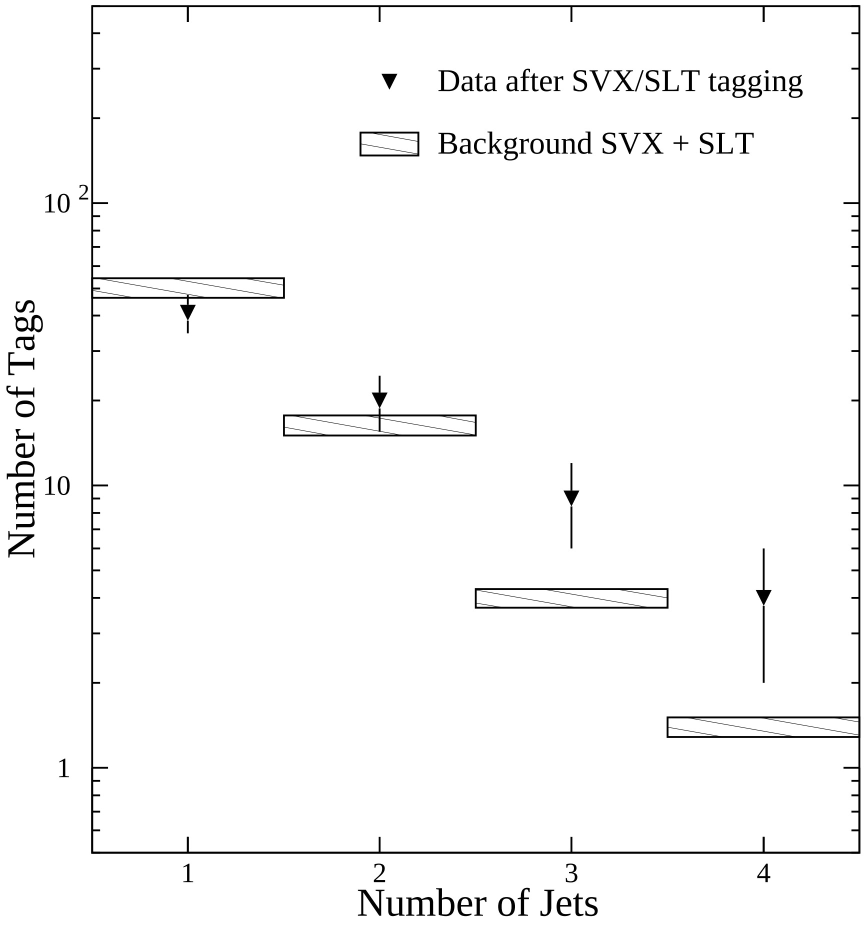
Gives a smaller overall SVX background

Sample	SVX bkg (I)	SVX bkg (II)	SVX tags
W+1 jet	15.8 ± 2.1	10.6 ± 3.7	8
W+2 jet	6.3 ± 0.8	4.3 ± 1.4	8
W+$\geq$ 3 jet	2.30 ± 0.29	1.44 ± 0.54	6

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

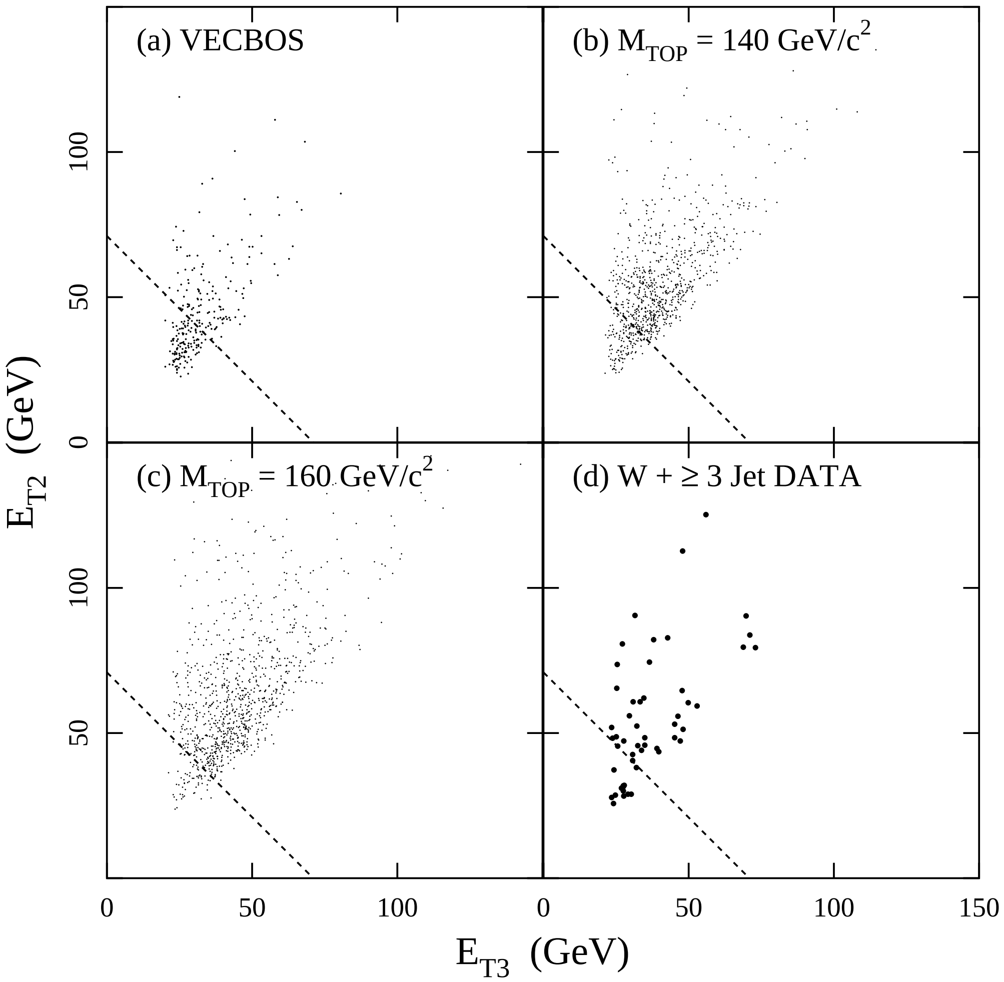
If we use the theoretical prediction for the $W + b\bar{b}$ background

- Overall significance is 2.6×10^{-4} estimate

Kinematic Features of Events

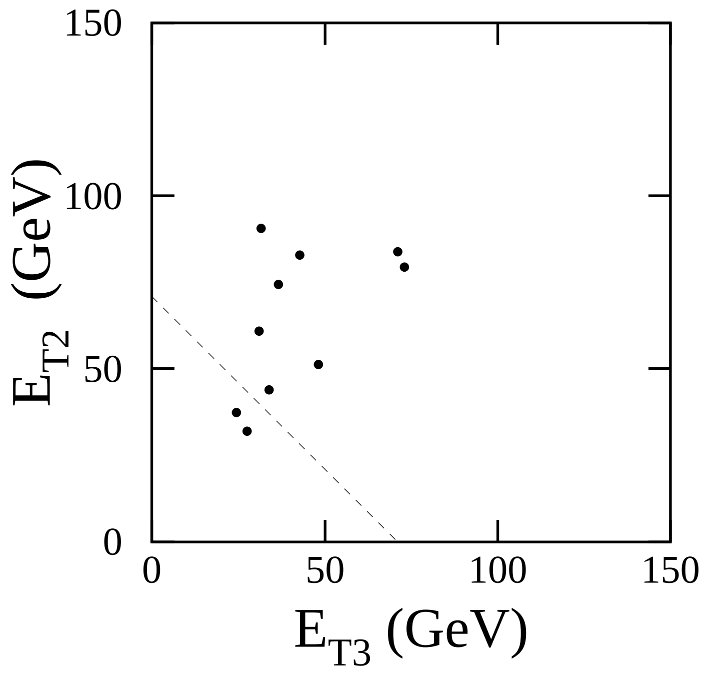
We have also looked at various kinematic features of events

- 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

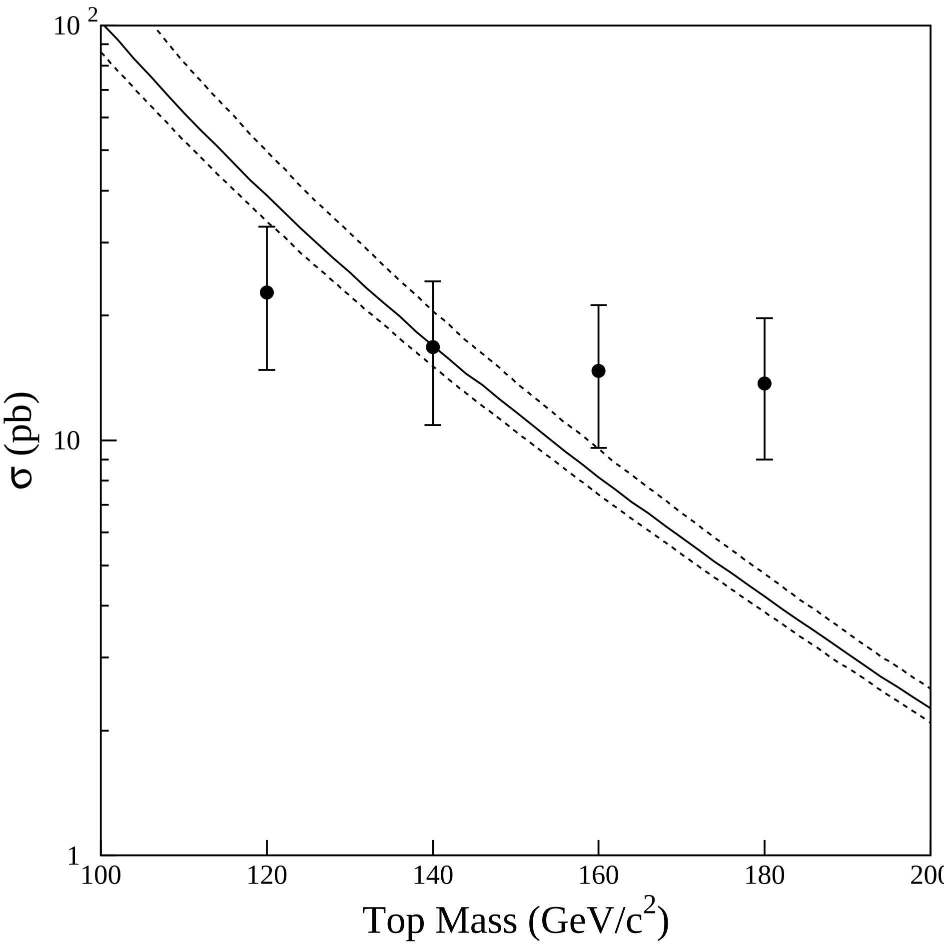
- ~ 20 events from $t\bar{t}$ production
- remainder mostly QCD $W+$ jets
- Confirmed by looking at E_{T2} versus E_{T3} for tagged sample



Cross Section for Top Production

Can use our data to estimate top quark cross section

- Subtract the expected backgrounds
  - Have to "bootstrap" using the tagging efficiencies
  - 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 can use the 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

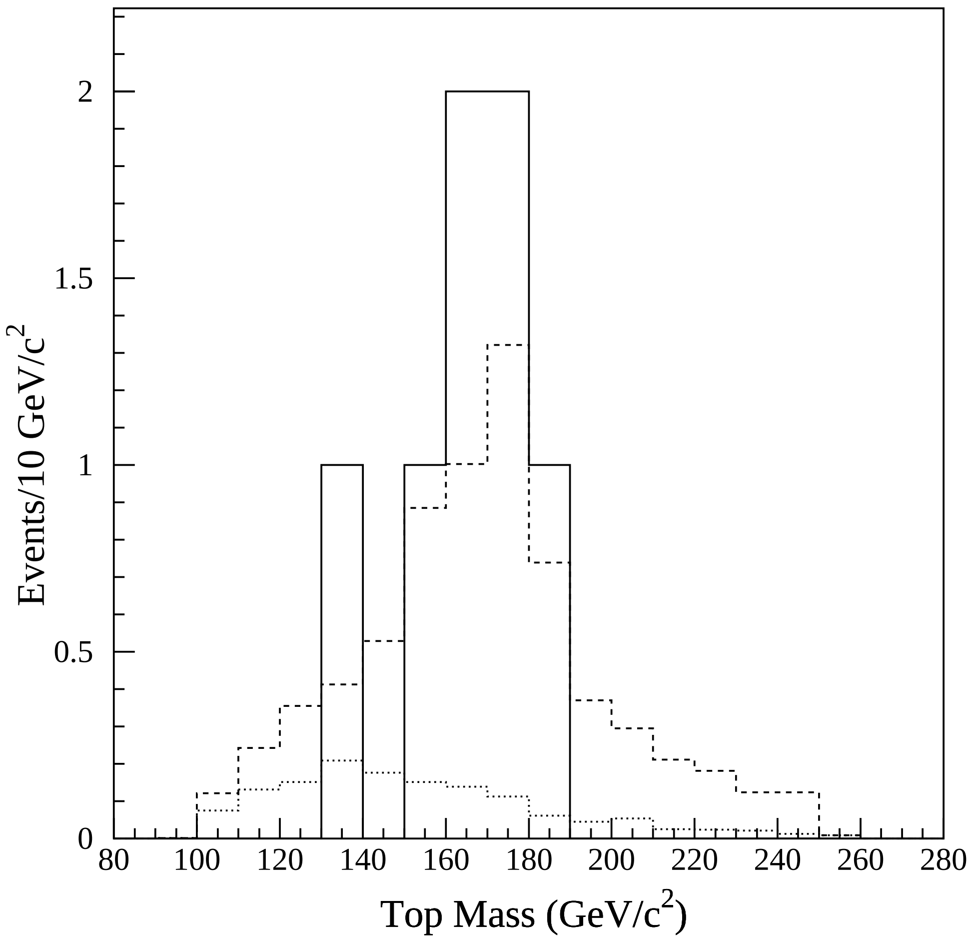
This selection leaves us with 7 tagged events

- Background estimate is $1.4^{+2.0}_{-1.1}$ events
  - Primarily QCD W+jet

Procedure is very dependent on theory predictions

Result of Mass Fits

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



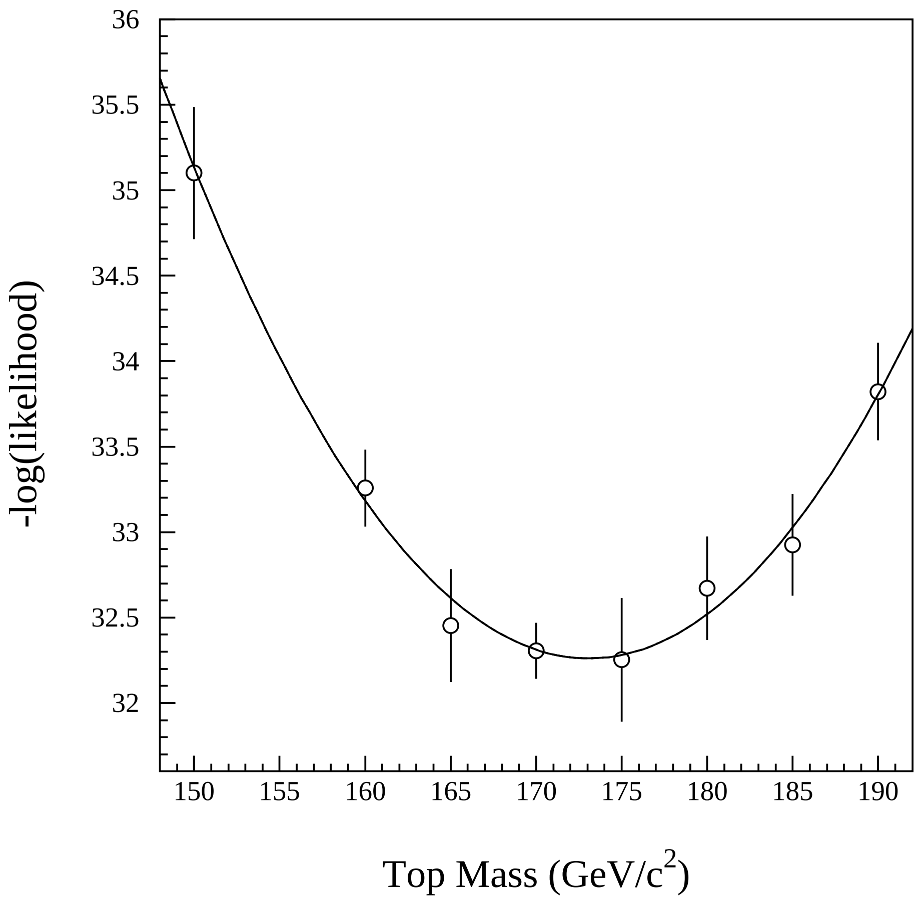
Fit the mass distribution to obtain

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

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)

Log Likelihood Plot



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. Cannot rule out very exotic scenarios (eg. H^+)
   - Will simply need more data

Most probably interpretation is that we are seeing top

Note that D0 does not confirm our claim

- But they don't have sensitivity to this top mass either

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	Number of 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 generating collisions in January 1994

- Run for another ~ 12 months
- Double maximum luminosity to 1.5×10^{31} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Goal is for CDF/D0 to collect ~ 75 pb^{-1}

This will allow us to confirm the "top" signal

- After 3 pb^{-1} have a new $e^-\mu^+$ event
- Expect to have necessary confirmation by end of 1994
- Start studying top decay modes and other properties

$\boxed{\textbf{Conclusions}}$

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

More data (coming!) is required to establish claim