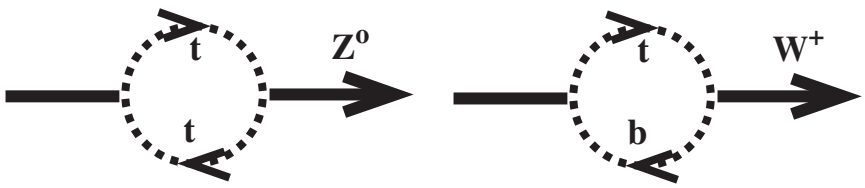
SM Predictions for Top Quarks

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 dominate decay $t \rightarrow W^+ b$

$W^\pm$ and Z° masses depend on heaviests fermions



- LEP, SLD measurements on the Z resonance require

$$M_{top} = 179 \pm 9^{+17}_{-19} \text{ GeV/c}^2$$

D. Schaile, 1995 $p\bar{p}$ Topical Conference

Top Quark Phenomenology

Top Quarks decay via the weak force

- Predict $\sim 100\%$ $t \rightarrow W^{+} b$
- Lifetime depends on mass

$$\Gamma_t = \frac{G_F M_{\text{top}}^3}{8\sqrt{2}\pi} \left(1 - \frac{M_W^2}{M_{\text{top}}^2}\right)^2 \left(1 + 2\frac{M_W^2}{M_{\text{top}}^2}\right)$$

- For heavy top ($M_{top} \gtrsim 100 - 120$ GeV/c^2), decays before it hadronises

Sensitive to some classes of "new physics"

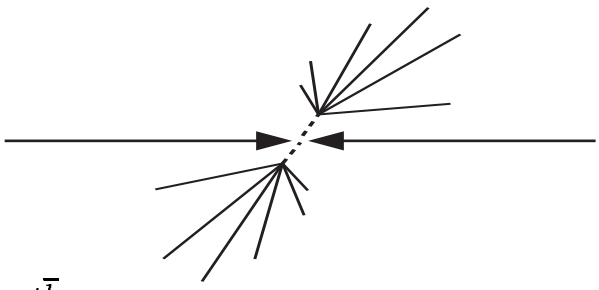
- Higgs couples strongly to top
- Could decay into a SUSY H^{+}

$$t \rightarrow H^{+} b$$
$$\hookrightarrow \tau^{+} \nu_{\tau}$$

What Do We Already Know About Top?

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

F.Abe et al. (CDF), PRL **73**, 220 (1994).

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).

S. Abachi et al. (DØ), PRL **72**, 2138 (1994).

Production of Top in Hadron Collisions

Top quark production is mediated by

$$q\bar{q}, gg \quad \rightarrow \quad t\bar{t}$$

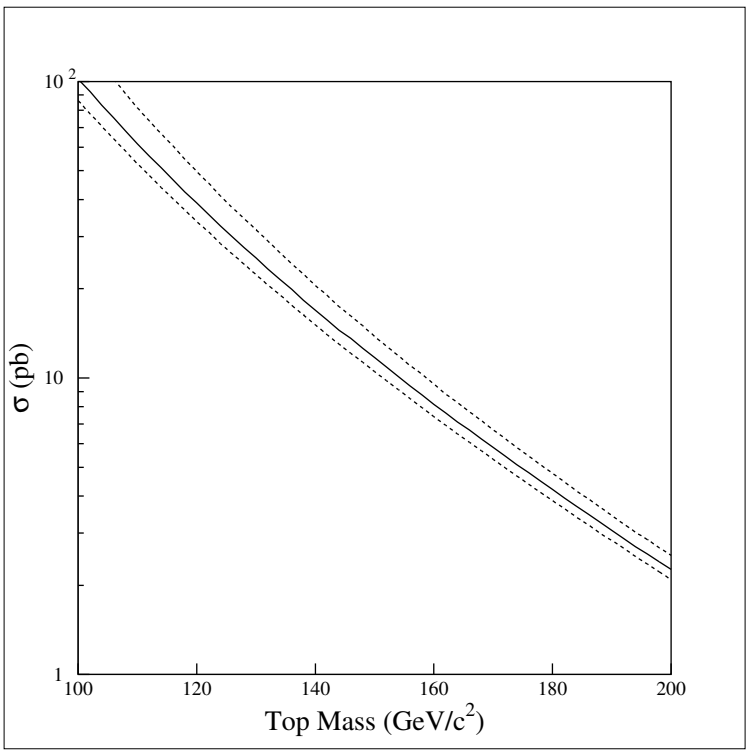
$q\bar{q} \rightarrow t\bar{b}X$ and $q\bar{q} \rightarrow W^+ \rightarrow t\bar{b}$ both small

Because top is heavy, need large x for initial partons

- Implies that cross section falls with mass
- $t\,\bar{t}$ system approximately at rest – $< P_T > \sim M_{top}/2$

Higher order corrections to $\sigma_{t\,\bar{t}}$ have been calculated

- Most recently by Laenen, Smith and Neerven, NP **B369**, (1992) 543.
- Biggest effects due to "soft gluon emission"



Top Decays and Detection Requirements

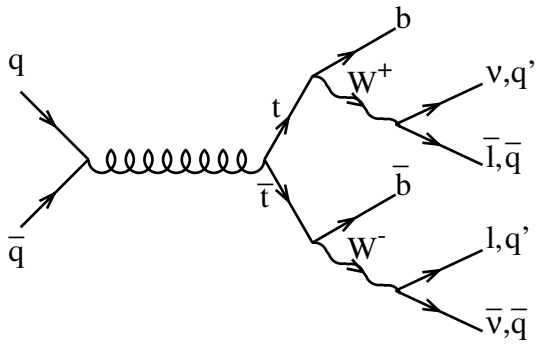
SM top quark decays via the weak force

$$t \rightarrow W^+ b$$

$$\hookrightarrow u\bar{d} \text{ or } c\bar{s} \quad (2/3)$$

$$\hookrightarrow e^+\nu_e \text{ or } \mu^+\nu_\mu \text{ or } \tau^+\nu_\tau \quad (1/3)$$

In proton-antiproton collisions,



This results in several distinct decay signatures

- Six jet final states (36/81)
- Lepton ($e^\pm$ or $\mu^\pm$) + Jet events (24/81)
- Dilepton events with 2 energetic $e^\pm$ and $\mu^\mp$ (4/81)
- Decay modes with τ's hard! ($\sim$ 12/81)

Detector Requirements

Detection of these decay modes requires

- Good jet reconstruction (energy and direction)
- Good lepton ID capability (acceptance and efficiency)
  - $> 80 - 85\%$ is reasonable
- Missing energy detection (for neutrinos)

Production/decay properties imply that

- Production is "central" (especially for high mass)
- Most likely initial state is where $x_1 \sim x_2$
- Top quarks are produced with modest P_T

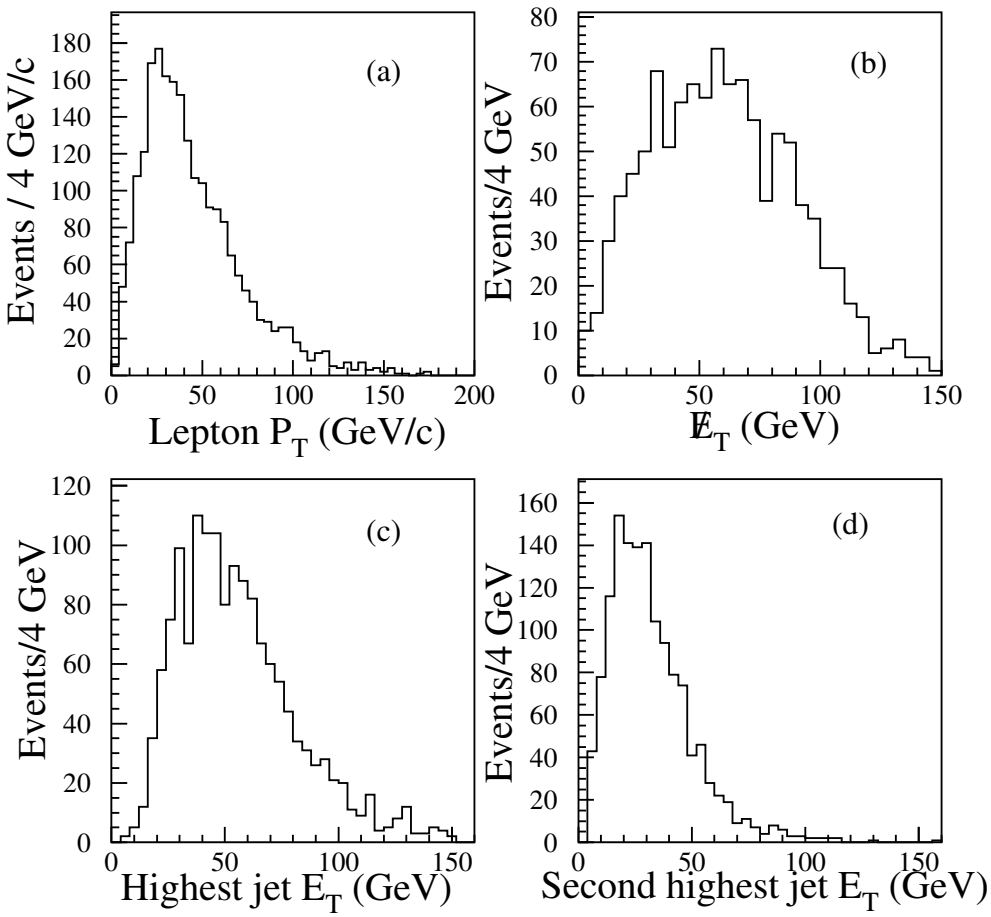
  $\Rightarrow$ daughters are isotropic in lab frame

Detector requirements boil down to

1. Coverage over $|\eta| \lesssim 2 - 2.5$ desirable
2. Good efficiency for partons with $P_T \geq 15 - 20$ GeV/c
3. Good lepton ID with high efficiency

Can see this from $t\bar{t}$ MC

- $M_{top} = 160$ GeV/c^2 in dilepton channel
- Plot observed jet and lepton energies



Background Considerations

The backgrounds are dominated by QCD processes

- Multi-jet final states direct background to 6-jet channel
- Jets faking leptons potential background to lepton ID
- Many SM EWK physics processes
  - Drell-Yan production in e^+e^- and $\mu^+\mu^-$ modes
  - Z° production
  - Semi-leptonic bottom and charm quark decays
  - QCD $W+$ jet processes
  - Di-vector boson final states: W^+W^-, W^+Z°

Any of these could compromise one of the searches

- Lepton ID must have extremely good jet-rejection
- Kinematics of background events must be used
  - For example, can use P_T and lepton isolation requirements to reduce and characterise b, c quark production

Background Studies Extremely Important

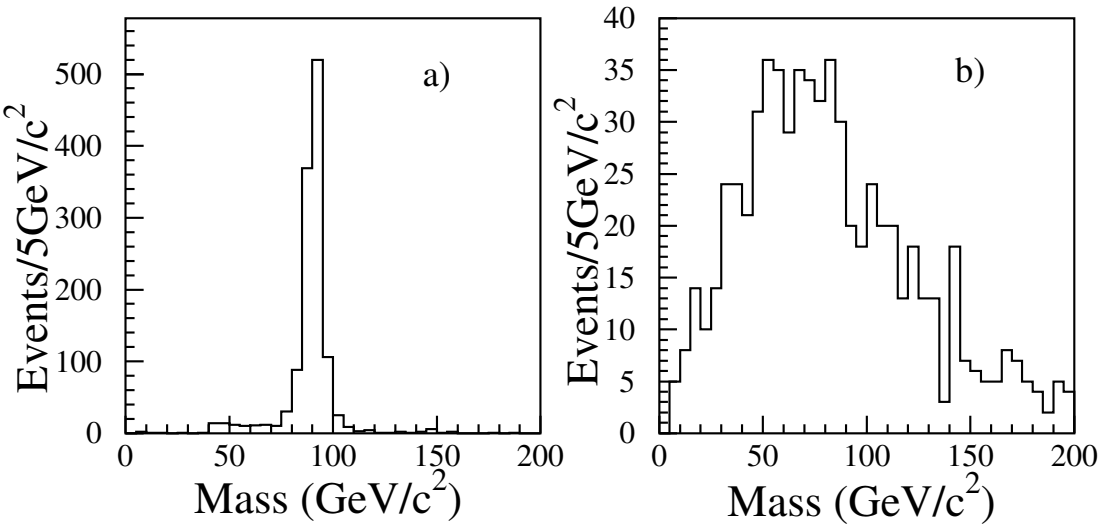
Dilepton Top Quark Search

$t\bar{t}$ 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

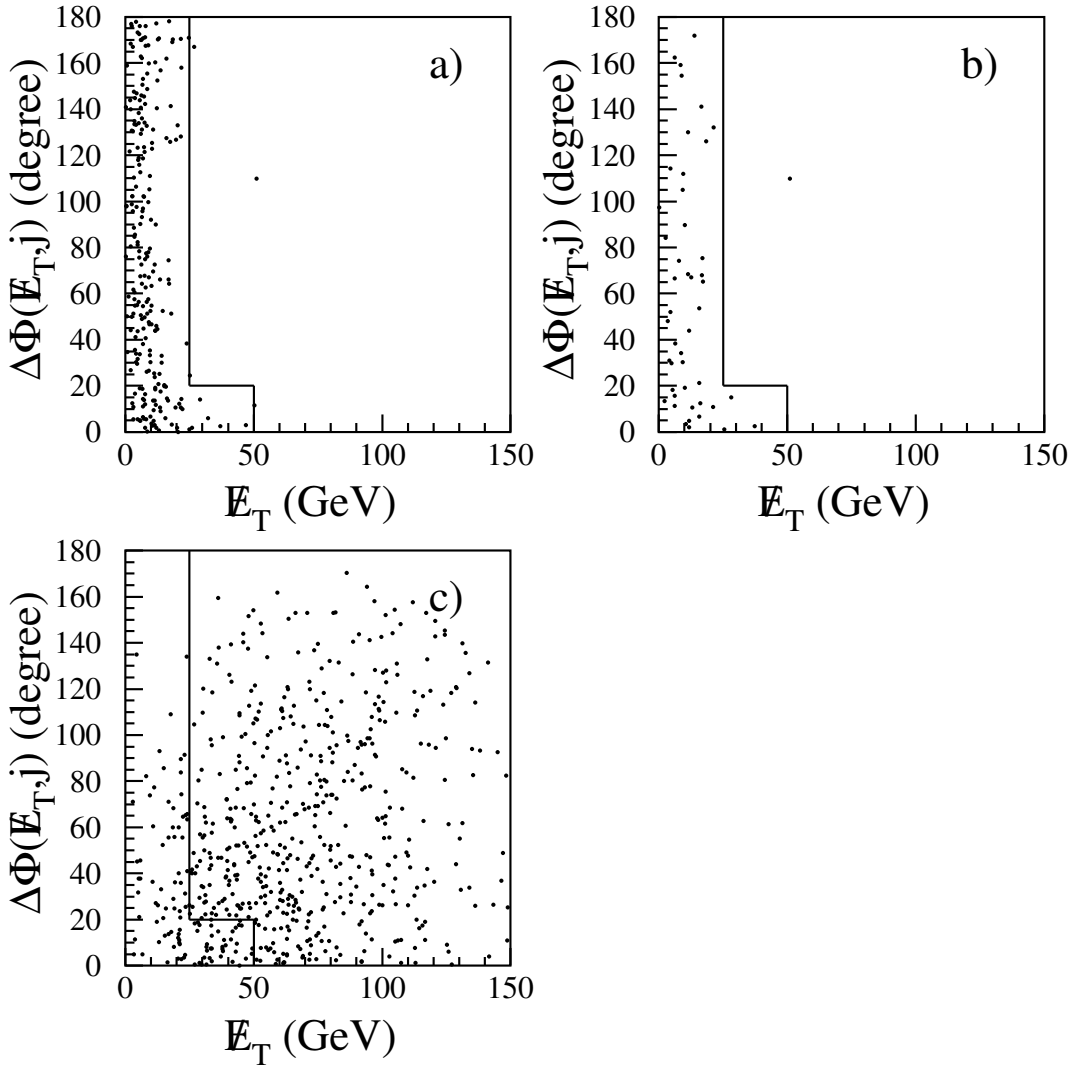
CDF performs search requiring

- 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°)



Significant dilepton background is Drell-Yan production

- $\not\!\!E_T$ signature created by mismeasured jet
- Harden $\not\!\!E_T$ cut to > 50 GeV if correlated with jet



a) Z+1 jet, b) Z+ 2 jet, and c) $t\bar{t}$ ($M_{\text{top}} = 160$ GeV/c^2)

Example: CDF $Z \to \tau^+\tau^-$ Background

The $Z \to \tau^+\tau^- \to e^+\mu^-\nu_e\bar{\nu}_\mu X$ is largest background for all dilepton channels

- Take sample of observed $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events
  - Gives correct Z kinematics
  - Gives correct associated jet production
- Replace each lepton with a $\tau^\pm$
  - Use MC to decay $\tau^\pm$
  - Use detector simulation on $\tau^\pm$ decay daughters

Resulting calculation is relatively model-independent

- MC model dependence very small
- Limited by Z statistics

Jet Cut	e^+e^- and $\mu^+\mu^-$	$e^\pm\mu^\mp$
Jet $E_T > 10$ GeV	0.17 ± 0.05	0.21 ± 0.05
Jet $E_T > 15$ GeV	0.10 ± 0.03	0.13 ± 0.04

Results for Dilepton Channel

Have measured the rate of events from non-top sources

- Used data to measure most of these rates
- Cross-checked using $Z^{\circ} \rightarrow e^{+}e^{-}$ and $Z^{\circ} \rightarrow \mu^{+}\mu^{-}$
- Consistent with theoretical calculations

Background	**e**μ (events)	**ee**, $\mu\mu$ (events)
$Z \rightarrow \tau^{+}\tau^{-}$	0.21 ± 0.05	0.17 ± 0.05
One or both leptons fake	0.10 ± 0.10	0.13 ± 0.10
$b\bar{b}$	0.01 ± 0.01	0.02 ± 0.01
WW, WZ and ZZ	0.13 ± 0.06	0.08 ± 0.03
Drell-Yan		0.44 ± 0.28
Total	0.45 ± 0.14	0.84 ± 0.28

- Expect 1.3 ± 0.3 background events

Control of Backgrounds

Evolution of background rates in dileptons instructive

Run Period	Sensitivity (pb^{-1})	Bkg σ (fb)	Comments
1988-89	4	350	Just dilepton requirement
CDF 1A	20	20	More Drell-Yan rejection
CDF Run 1A/B	67	19	Added ≥ 2 jet cut
DØ 1A	15	72	≥ 1 jet (for $M_{top} < 120$)
DØ 1A	15	52	≥ 2 jets (for $M_{top} > 120$)
DØ 1A/B	44-56	14	Added H_T cut

Have to be careful with background studies

- Data fluctuations can lead to "carving up" of acceptance
- Base cuts on independent samples
- Use MC predictions to guide

What Is Expected From Top

Expected number of $t\bar{t} \rightarrow$ dileptons is determined using MC and full detector simulation

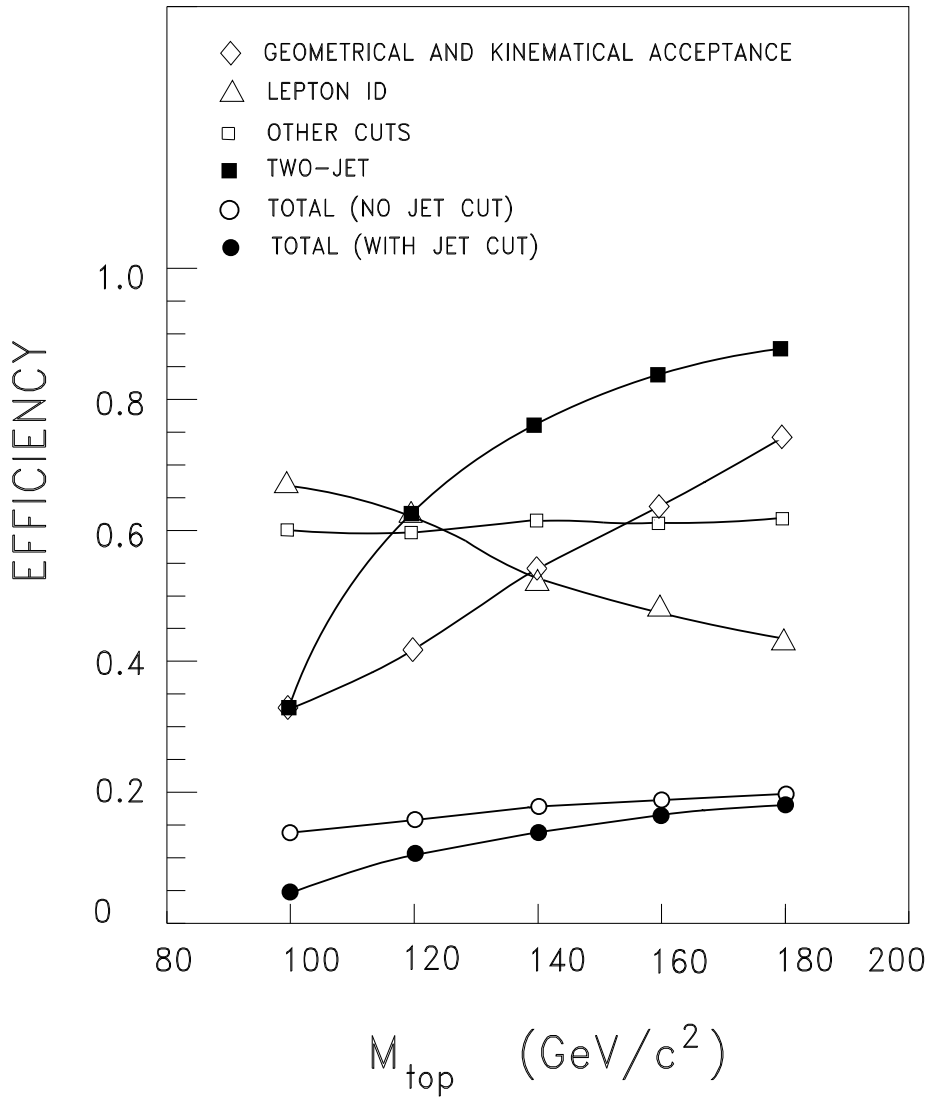
M_{top} (GeV/c^2)	$\sigma_{t\bar{t}}$ (pb)	Events Detected
160	8.2	4.4
170	5.8	3.0
180	4.2	2.4

Breakdown by channel reflects branching ratios

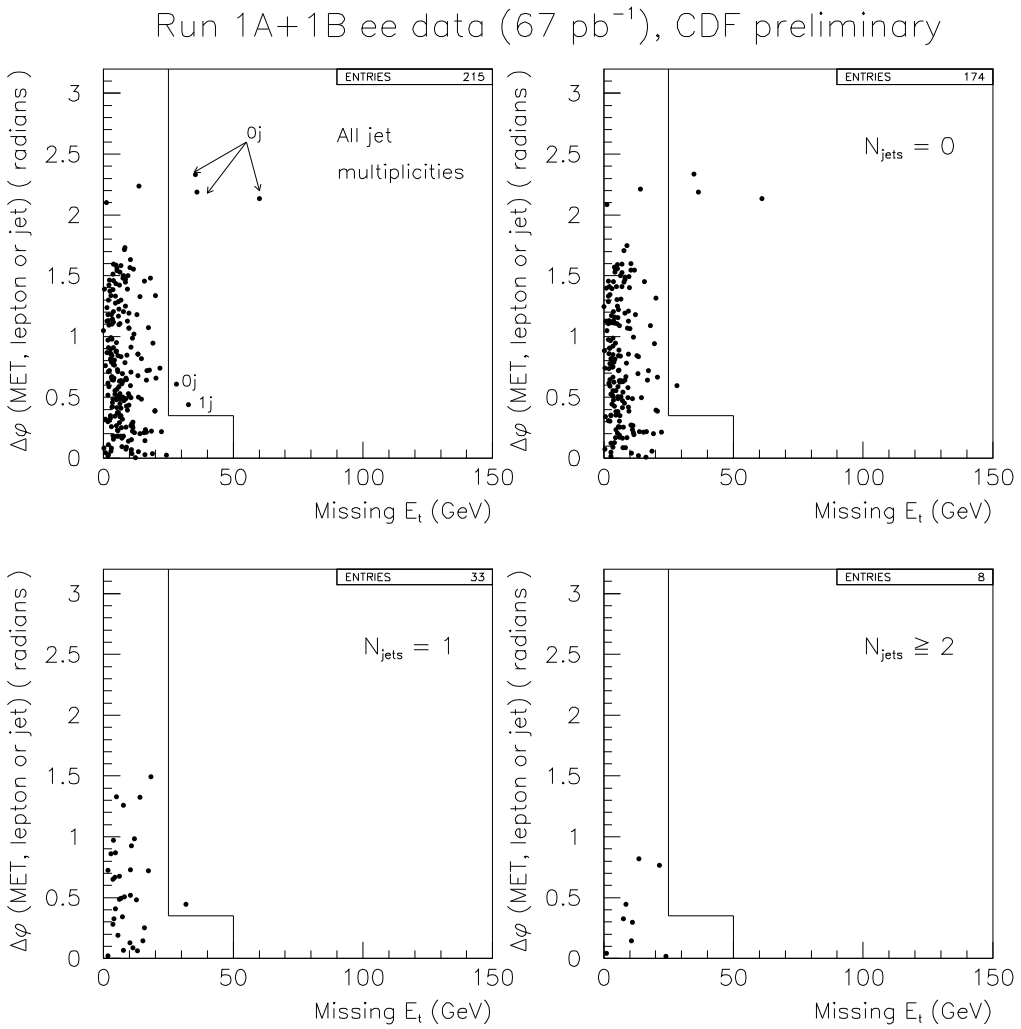
Channel	Signal Fraction
$e\mu$	57%
ee	20%
$\mu\mu$	23%

M_{top} of 170 GeV/c^2 assumed

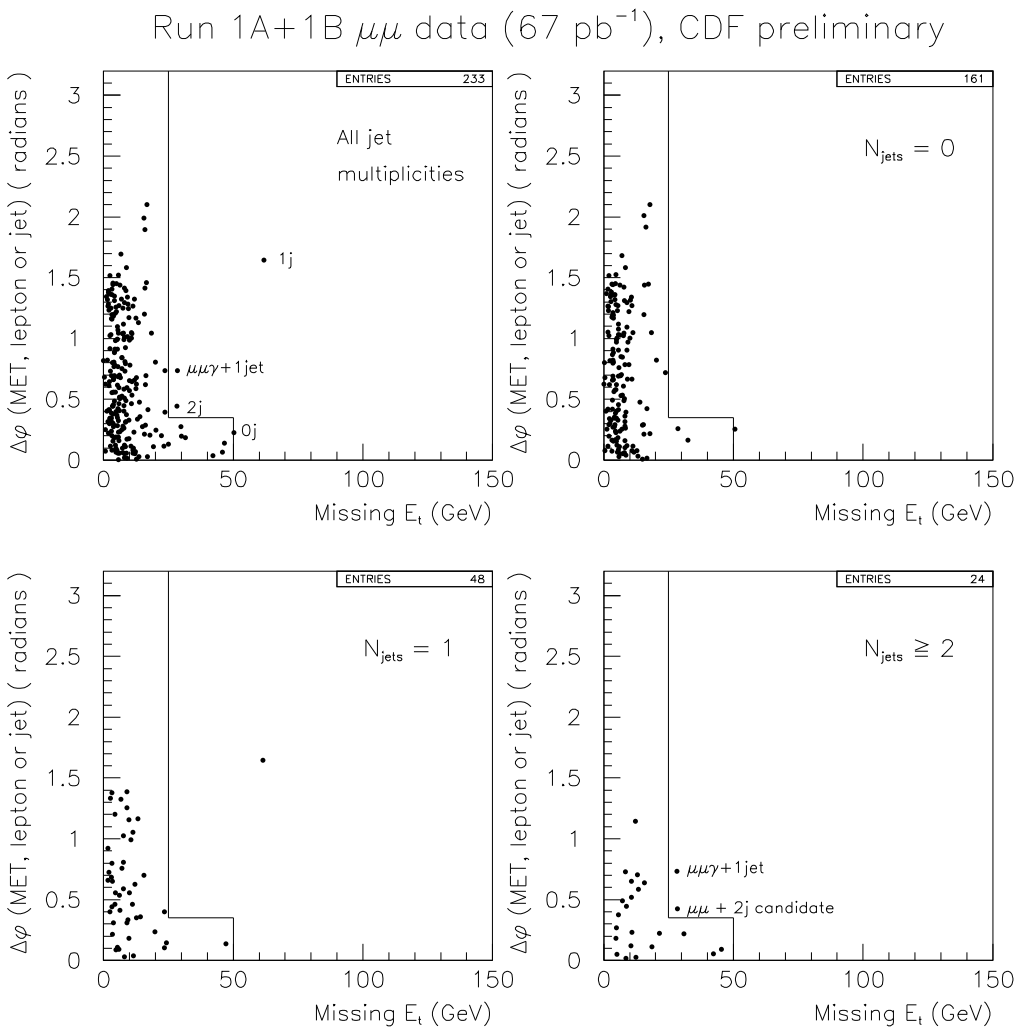
Dilepton acceptance as a function of top mass



Dielectron Data for Run 1A and 1B

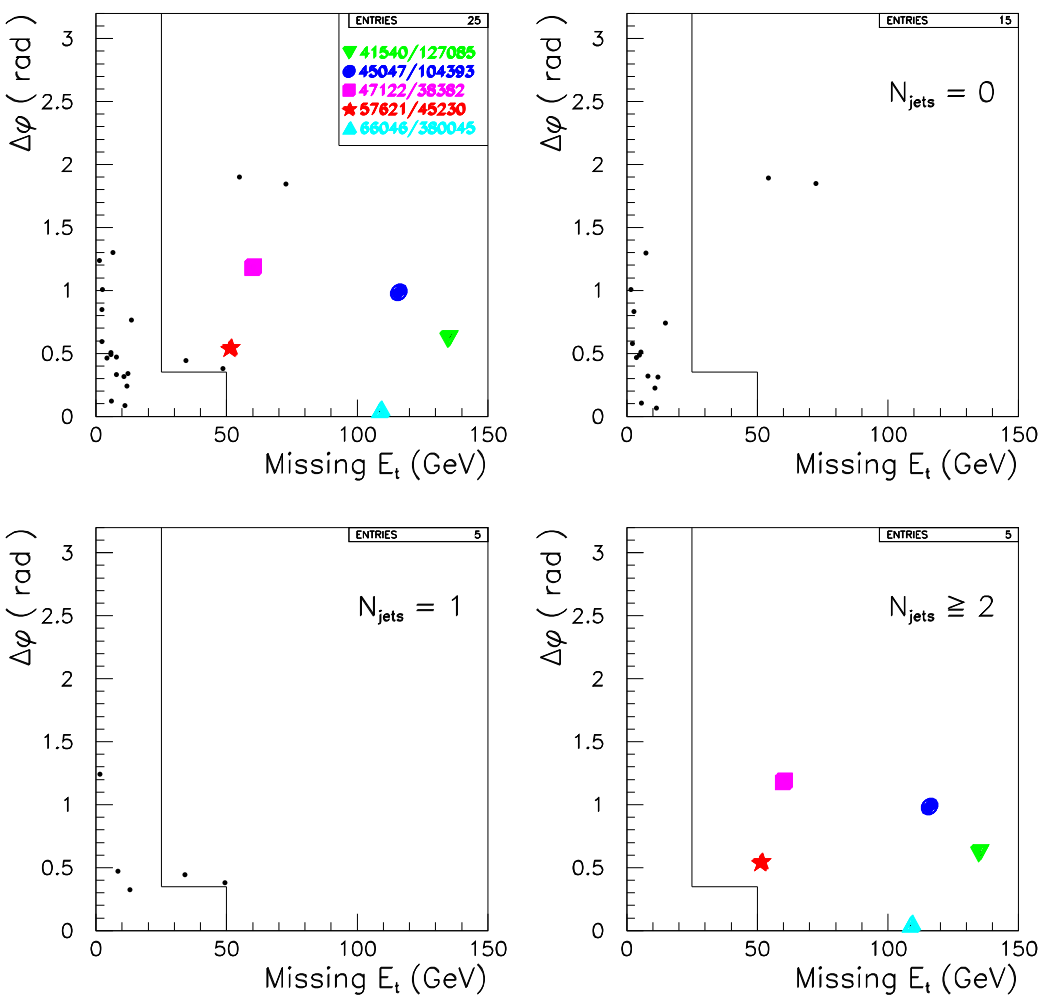


DiMuon Data for Run 1A and 1B



Electron-Muon Data for Run 1A and 1B

eμ data: Δφ (MET, lepton or jet) vs Missing E_t



Summary of CDF Dilepton Search

Observe a total of 6 candidate events

- Observe 1 $\mu^+\mu^-$ event and 5 $e\mu$ events
  - Additional $\mu^+\mu^-$ event excluded
  - Has $\mu^+\mu^-\gamma$ mass close to Z°
- Expect 1.3 ± 0.3 events from background

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

This means:

- "If experiment is repeated and top **doesn't** exist, then fraction of experiments with at least 6 events observed is 1 in 300."

B Quark Tags in CDF Dilepton Events

Can *a posteriori* check for evidence of b jets

- Use SVX and SLT algorithms described later
  - Two events with SVX-SLT "double tags"
  - One event with SLT μ tag

- Would expect 0.47 tags if no b quark jets
  - Would expect 3.6 tags if all 6 are $t\bar{t}$

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 to "tag" neutrino

Problems come from physical backgrounds

- Backgrounds from "fake" leptons, etc. are manageable
- "QCD W + jet" production much larger than $t\bar{t}$
- Have to find additional rejection power
  1. Place more stringent kinematical requirements
  2. Require presence of b quark jet
     - "tag" semileptonic b quark decays
     - "tag" using large $c\tau$ of b decays
       * This capability is unique to CDF
- Have to maintain good top efficiency

W+Jet Selection

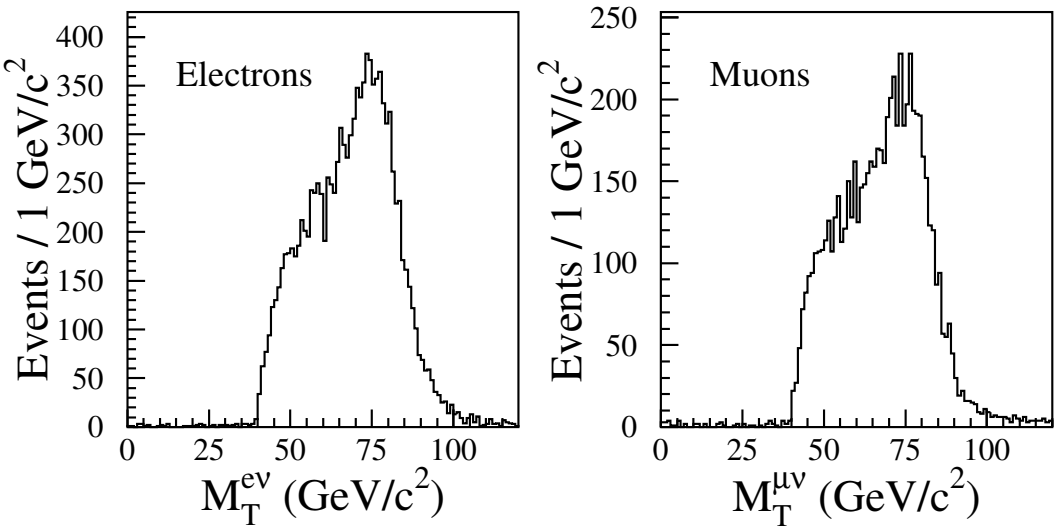
Selection of W candidates straightforward

- Require high P_T isolated lepton candidate
- Require significant $\not\!\!E_T$
- Require three or more high P_T jets

One obtains a large inclusive W samples

- CDF has 31,000 $e\nu_e$ and 21,000 $\mu\nu_\mu$ candidates

Run 1A CDF data shows clear "W" signal:



W + Jet Sample

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

- $\geq$ 3 jets with $E_T > 15$ GeV and $|\eta| < 2.0$
  - finds 203 W+$\geq$ 3 jet events

Most background sources are small:

Background	Number of Events (CDF)
Fake leptons and $b\bar{b}$	18 ± 9
WW, WZ and ZZ	9 ± 4
$Z \rightarrow \tau\tau$, ee, $\mu\mu$	15 ± 3
Total	42 ± 10

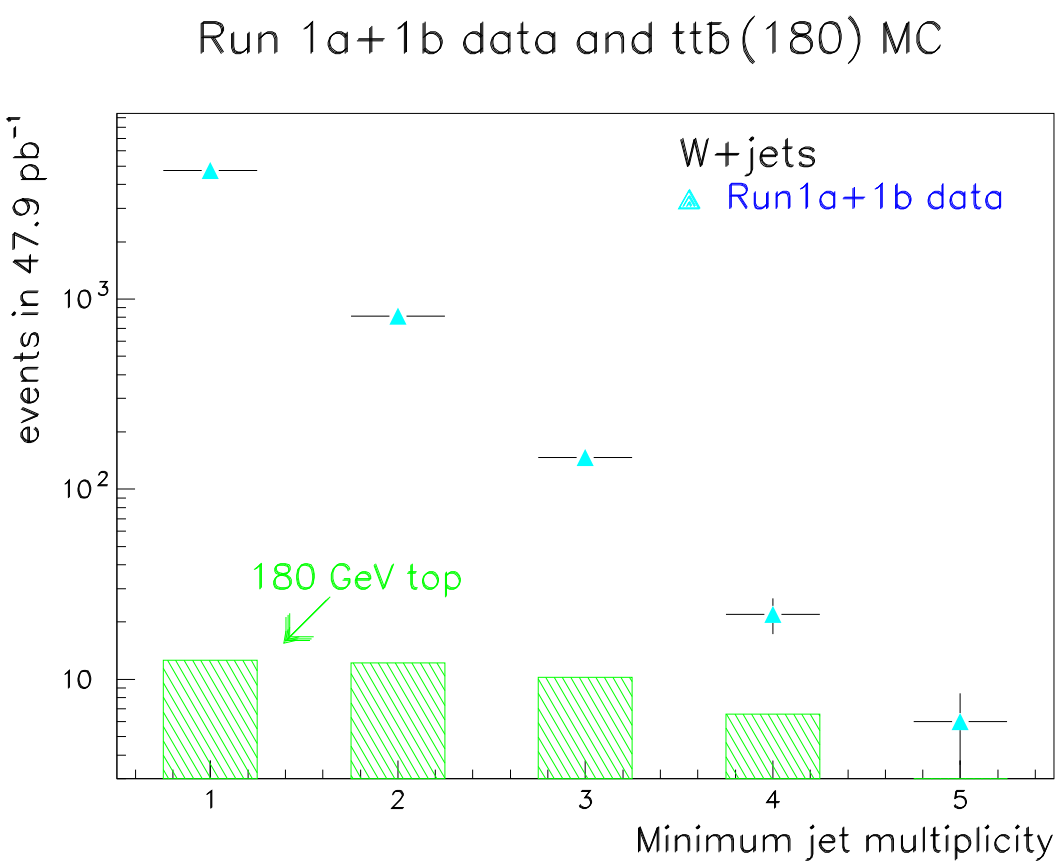
QCD W+jets production is largest expected background

M_{top} (GeV/c^2)	Number of Events (CDF)
120	136 ± 21
140	77 ± 10
160	42 ± 7
180	23 ± 2.4
W+jets	175^{+56}_{-28}

Jet Multiplicity

Following plot illustrates the serious S/N problem

- Event distribution versus minimum jet multiplicity
- Require jet $E_T >$ 15 GeV (corrected)



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 (SLT tags)
   - Expect about 15% of all $t\bar{t}$ events to have SLT

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

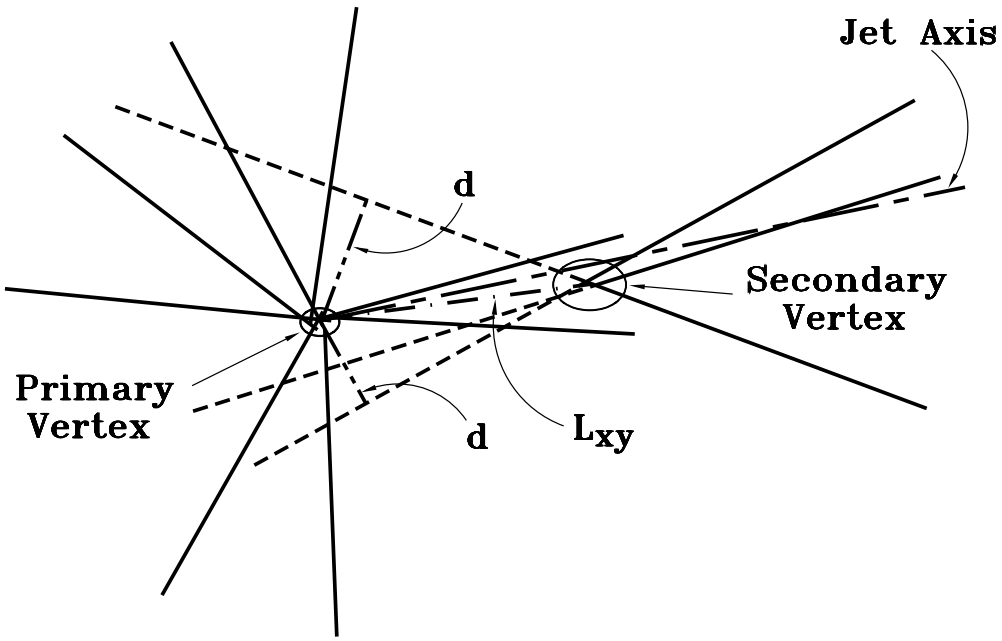
   - Use Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 42% of $t\bar{t}$ events to have at least one SVX tag

Idea is to just "count" number of tagged events

SVX B Tags

SVX tag requirements are

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



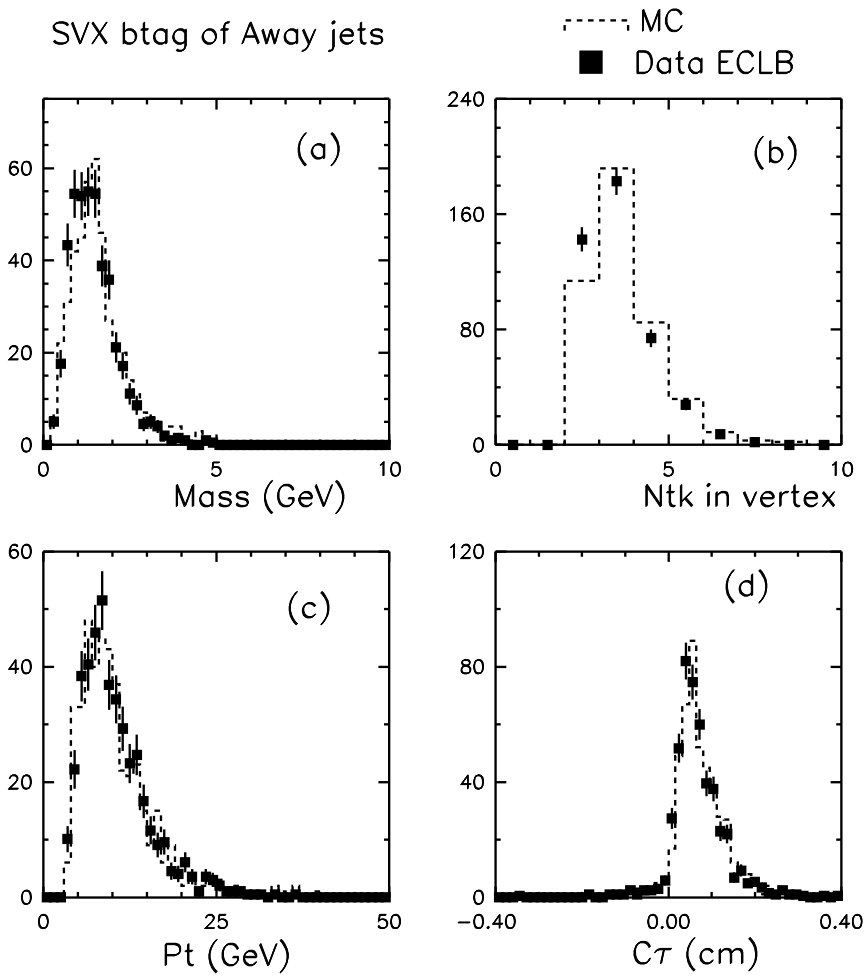
Used control samples to measure efficiency, fake rate

- 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

SVX B Tagging

Can demonstrate that tags are really finding b's

- Inclusive $e^{\pm}$'s are $\sim 40-60\%$ from $b \to e^{-}\nu_e c$
- Look at jet "away" from $e^{\pm}$ candidate
- See expected number of tags



SVX B Tagging Backgrounds

Can use rate of tags in QCD jet data to estimate background

- Multiply number of jets by per-jet tagging rate f_t
  - $f_t \sim 0.01$ and is independent of jet p_T
- This includes real $p\bar{p} \rightarrow bX$
- Include MC estimate for Wc production
- Does provide a conservative background estimate

More rigorous to separate background sources

- Fake tags estimated from rate of $-$ve decay length tags
  - Turns out to be ~ 0.003 tags per jet
- Tags from real heavy flavour ($Wb\bar{b}$ and $Wc\bar{c}$)
  - Use QCD matrix element for heavy flavour content
    - Use HERWIG and calculation by M. Mangano
    - CDF assigns a 100% uncertainty to rate
  - Use known tagging efficiencies
  - Calibrate against $W + 1$ and $W + 2$ jet data

Method I predicts larger background than Method II

- Use Method II as more reliable background estimate

Results for SVX Background Calculation

Can compare CDF results for Run 1B

- Summarise major sources of background below
- Estimates for CDF Run 1B data only
- Note that Wc background is added to both

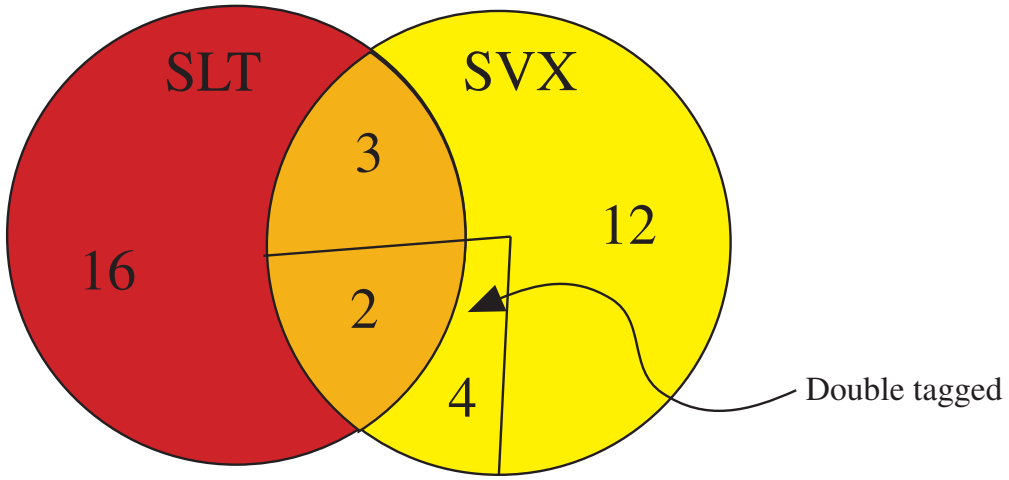
	$W+1$ jet	$W+2$ jet	$W+3$ jet	$W+\geq 4$ jet
Method 1	59 ± 7	20 ± 2	5.0 ± 0.7	1.6 ± 0.2
Fakes	10 ± 2	3.5 ± 0.7	0.9 ± 0.2	0.4 ± 0.1
$Wb\bar{b}$ $Wc\bar{c}$	11 ± 9	5.4 ± 4.3	1.4 ± 1.1	0.4 ± 0.3
Wc	12 ± 4	3.3 ± 1.0	0.7 ± 0.3	0.2 ± 0.1
Method 2	38 ± 10	15 ± 5	3.7 ± 1.2	1.1 ± 0.3

b Quark Tagging in W+Jet Events

Applied b 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	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



Summary of Counting Experiment

CDF sees significant excesses in all three channels

Channel	Background	Tags	Events	Prob
SLT	15.4 ± 2.0	23	22	6×10^{-2}
SVX	6.7 ± 2.1	27	21	2×10^{-5}
DIL	1.3 ± 0.3		6	3×10^{-3}

Probability of background $= 1 \times 10^{-6}$

Probability calculation performed by assuming no $t\bar{t}$

- "simulate" large number of experiments
- Count how many experiments would "see" more tags
- Properly takes into account
  - Uncertainties in background estimates
  - Correlations in uncertainties
  - Poisson fluctuations in total rate of events