Study of Top Quarks in Hadronic Interactions

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Lecture # 1 **Discovery of the Top Quark**

1. Hadron Colliders and Detectors
2. The Counting Experiments

Lecture # 2 **Top Quark Properties**

1. Cross section measurements
2. Production and Decay Kinematics
3. Mass and BR Measurement

Lecture # 3 **High Luminosity Top Studies**

1. Search for New Physics
2. High Statistics studies of Top
3. Future Top Quark studies

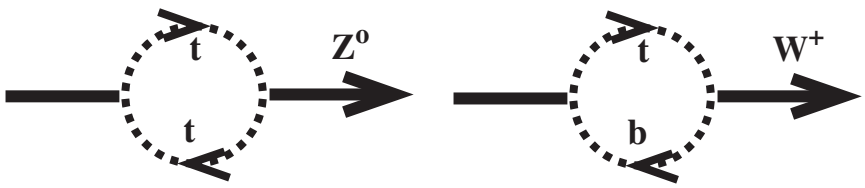
1995 SLAC Summer Institute

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% $t \to W^+ b$
- Lifetime depends on mass
- 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^+

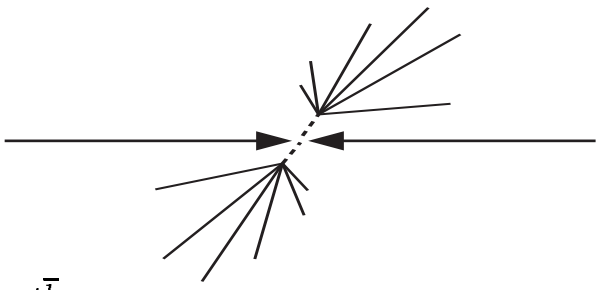
$$t \to H^+ b \quad \text{with} \quad H^+ \to \tau^+ \nu_\tau$$

- Top quark can be sensitive to SM details
  - V_{ts} CKM matrix elements
  - Constraints on other SM parameters (eg. A_{LR})
  - New physics that couples to $t\bar{t}$ system

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

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

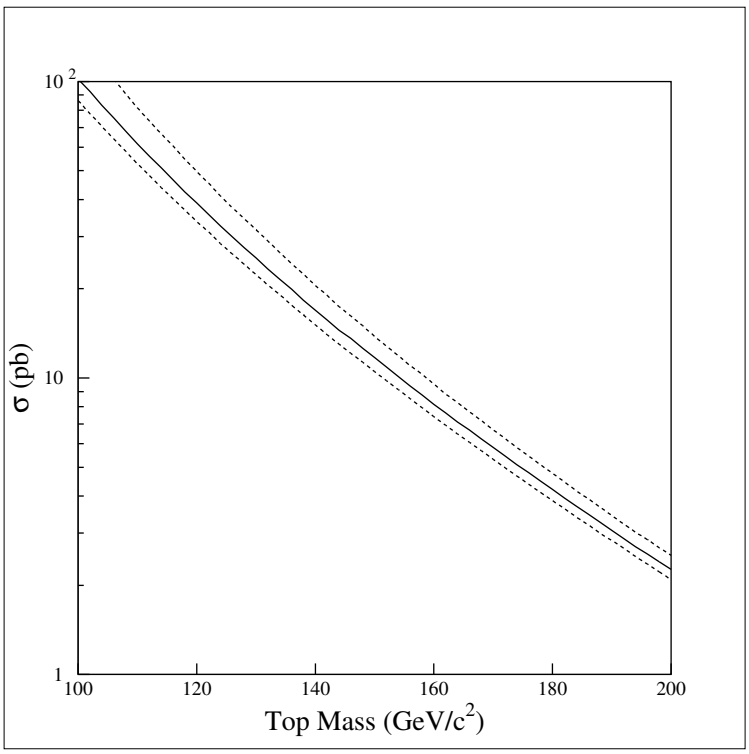
$q\bar{q} \rightarrow t\bar{b}X$ and $q\bar{q} \rightarrow W^+ \rightarrow t\bar{b}$ both small

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"

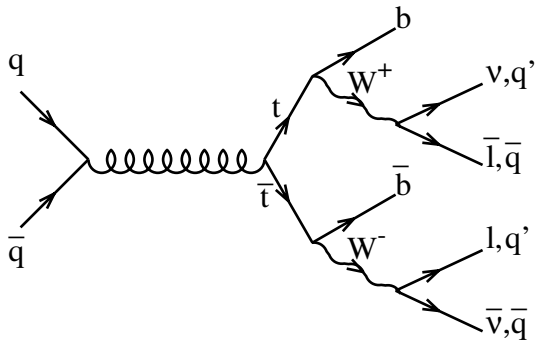


Top Decays and Detection Requirements

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

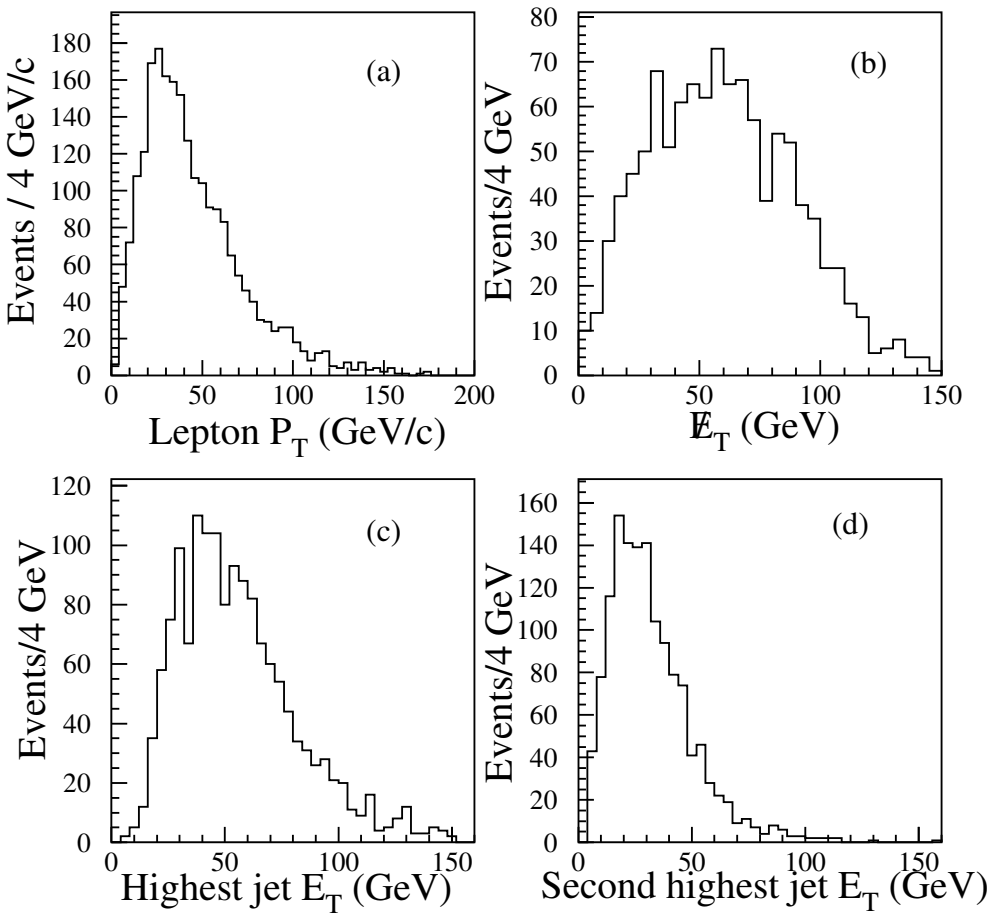
  $\Rightarrow$ daughters are isotropic in lab frame

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

The Fermilab Collider Experiments

CDF and DØ designed to study $\overline{p}p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Sophisticated general-purpose detectors operated by big collaborations

Main detector features:

- Hermetic Calorimetry
  - DØ has state-of-the-art Ur/Li Ar calorimeter
    - detection of $e^{\pm}$, γ and jets
  - CDF has more traditional Pb and Fe calorimeter
    - Scintillator readout for central region $|\eta| < 1.1$
    - Gas proportional chamber readout for plug/forward
  - Coverage over $|\eta| \lesssim 4.2$
  - Good hermiticity for $\not\!\!E_T$ measurement
  - Provides electron ID and jet detection

Resolutions	DØ	CDF
EM	$0.15\sqrt{E} \oplus 0.004E$	$0.13\sqrt{E} \oplus 0.02E$
$\pi^{\pm}, K^{\pm}$	$0.50\sqrt{E}$	$0.80\sqrt{E}$
$\not\!\!E_T x,y$	$1.08 + 0.019 \sum E_T$	

Detectors (continued)

- Muon chambers outside calorimeter
  - identify charge tracks that pass through calorimeter
  - DØ has toroidal magnets to measure muon P_T
    - $\Rightarrow \sigma_p/p \sim 0.18p$

- Central Tracking Systems
  - CDF has three-tiered system in 1.4 T field
    - Central Track Chamber (CTC) for $28 < R < 130$ cm
    - Vertex Chambers (VTX) in $10 < R < 23$ cm
    - Silicon Vertex Detector (SVX) in $3 < R < 12$ cm
    - $\Rightarrow \sigma_p/p \sim 0.001p$ (in GeV/c)
  - DØ has nonmagnetic central tracker
    - Also incorporates a Transition Radiation Detector (TRD) for electron ID

By design, detectors are complementary

- DØ emphasises calorimetery and muon ID
- CDF emphasises tracking and electron ID
- Reality is that both have strengths and weaknesses

Detector Limitations

CDF's dirty laundry"

- Muon system
  - not enough absorber
  - coverage somewhat fragmented
- Calorimetry
  - Not totally hermetic
  - Region $|\eta| > 3.6$ not well understood

DØ's laundry list:

- Trigger system still being shaken down
- Main ring backgrounds
- Lack of magnetic field reduces redundancy
  - Calibration more difficult
  - Not able to detect secondary vertices

Triggering Issues

Use multi-level trigger to tag events in real-time

- Interaction rate of

  $\left(50 \times 10^{-27}\ \text{cm}^2\right) \times \left(1.5 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}\right) = 7.5 \times 10^5$ Hz

  has to be reduced to of order 1-10 Hz

- Most challenging aspect of experiment
  - Depends critically on all subsystems
  - Need efficiency $> 75\%$ to be competitive

Triggering for "heavy" top is relatively easy

- Tag high P_T ($> 15 - 20$ GeV/c) lepton(s)
- Missing energy requirements ($\not\!\!E_T >$ 20 – 25 GeV)
- Multijet topologies
- Trigger efficiencies $\geq 90 - 95\%$ in most cases

1992-95 Collider Run

Tevatron Collider has been running since 1992

- Run 1A (1992-93) provided ~ 20 pb^{-1}
  - CDF scanned $\sim 1 \times 10^{12}$ collisions in 19.3 pb^{-1}
    - Collected 16×10^{6} events on tape
  - DØ collected 13.5 pb^{-1}

- Run 1B (1994-95) has produced another ~ 85 pb^{-1}
  - Run expected to continue till end of 1995
  - Show results from $50 - 70$ pb^{-1}

By far the largest and most sensitive dataset to top

- For a top quark with a mass of 160 GeV/c^2
  - $\sigma_{t\bar{t}} = 8.2$ pb $\Rightarrow$ 400 produced $t\bar{t}$ events
  - DØ and CDF would each expect to detect
    - ~ 6 dilepton events
    - ~ 20 lepton + jet events

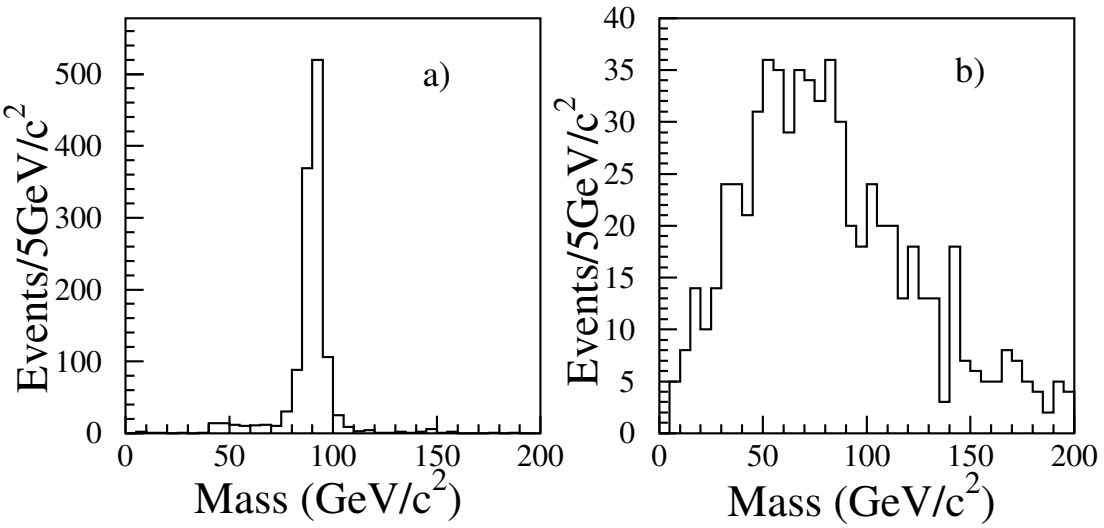
Dilepton Top Quark Search

$t\bar{t}$ 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

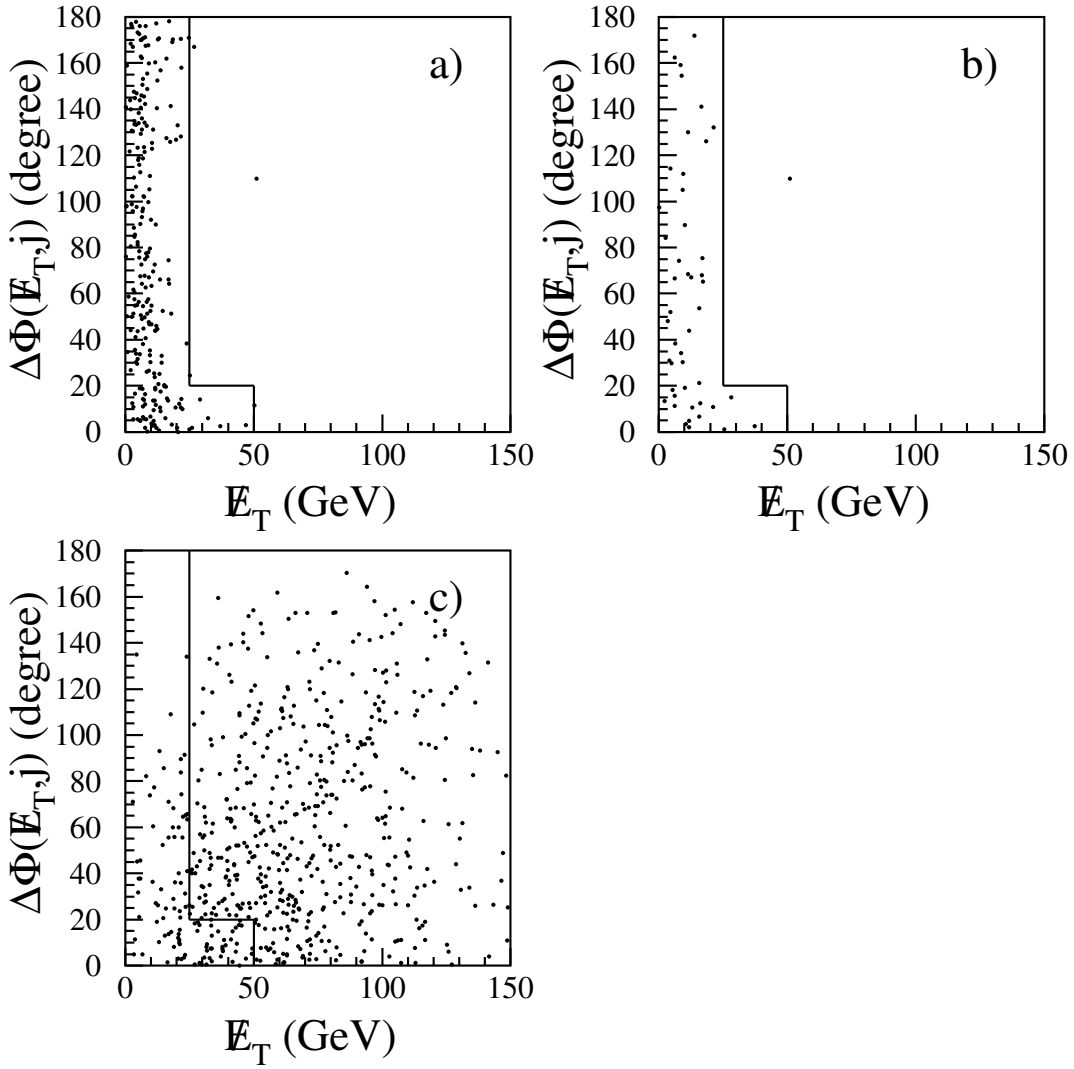
CDF performs search requiring

- 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

CDF 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

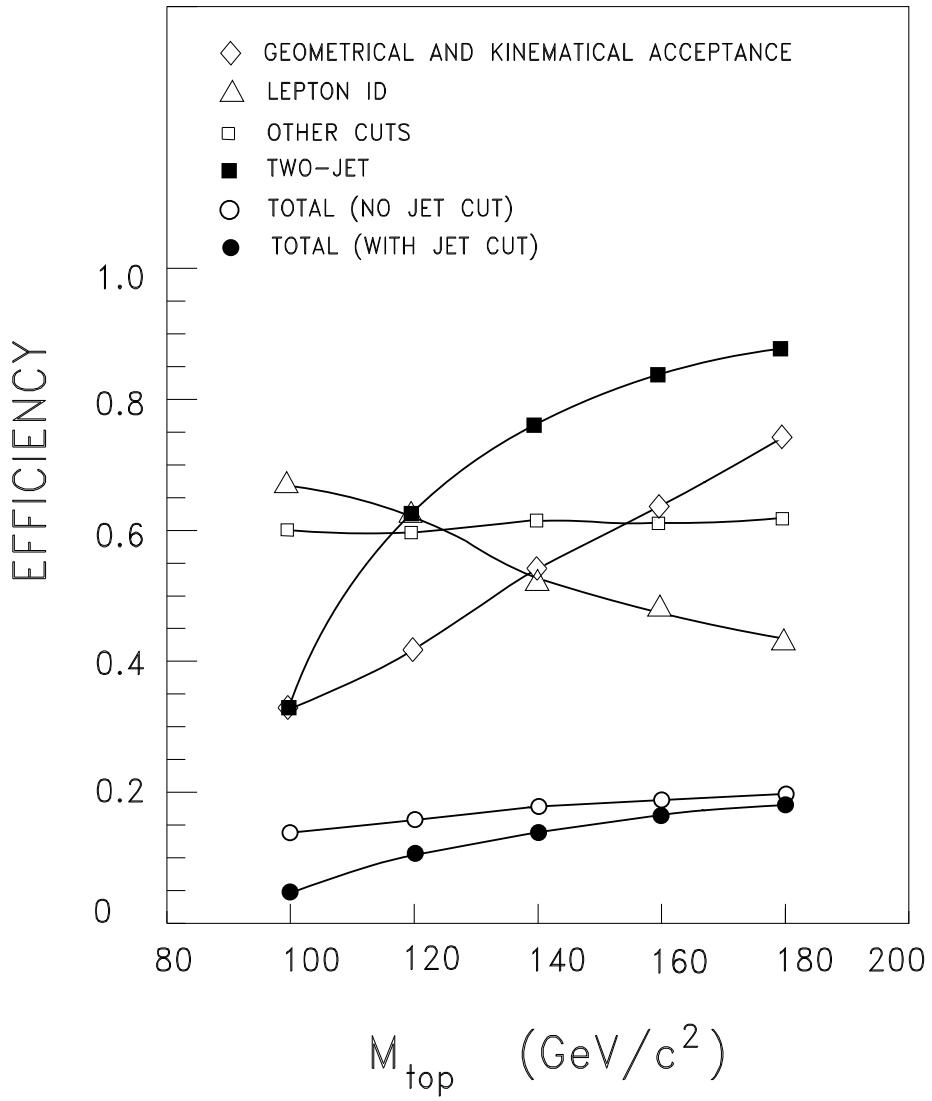
M_{top} (GeV/c^2)	$\sigma_{t\bar{t}}$ (pb)	Events Detected
160	8.2	4.4
170	5.8	3.0
180	4.2	2.4

Breakdown by channel reflects branching ratios

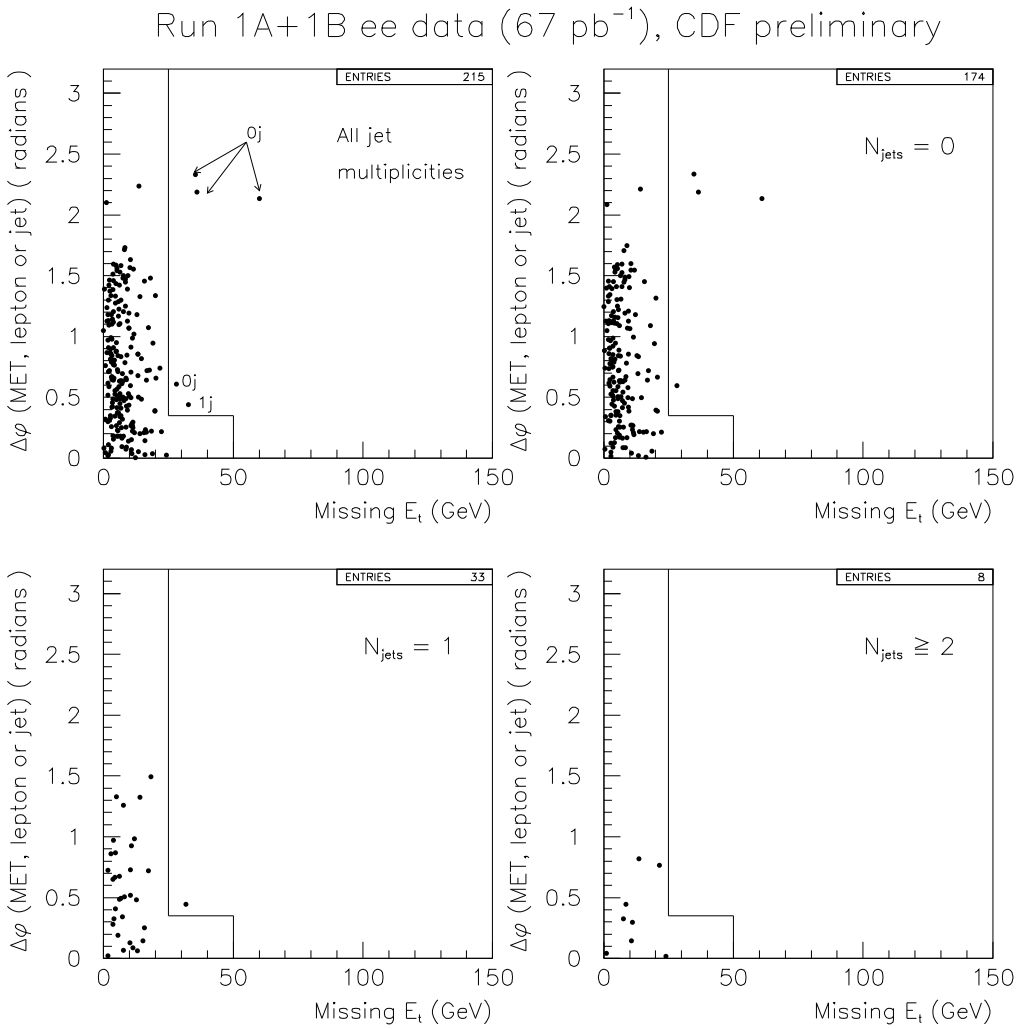
Channel	Signal Fraction
$e\mu$	57%
ee	20%
$\mu\mu$	23%

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

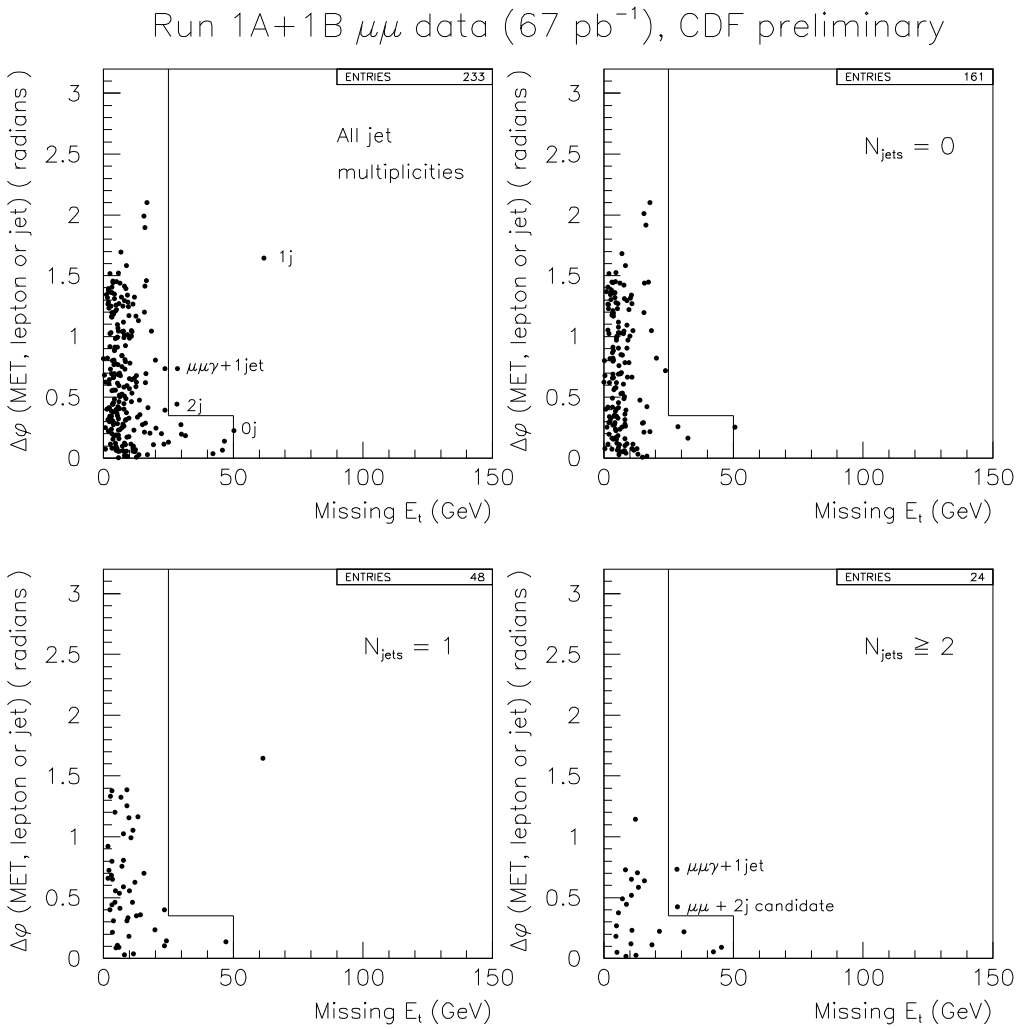
Dilepton acceptance as a function of top mass



Dielectron Data for Run 1A and 1B

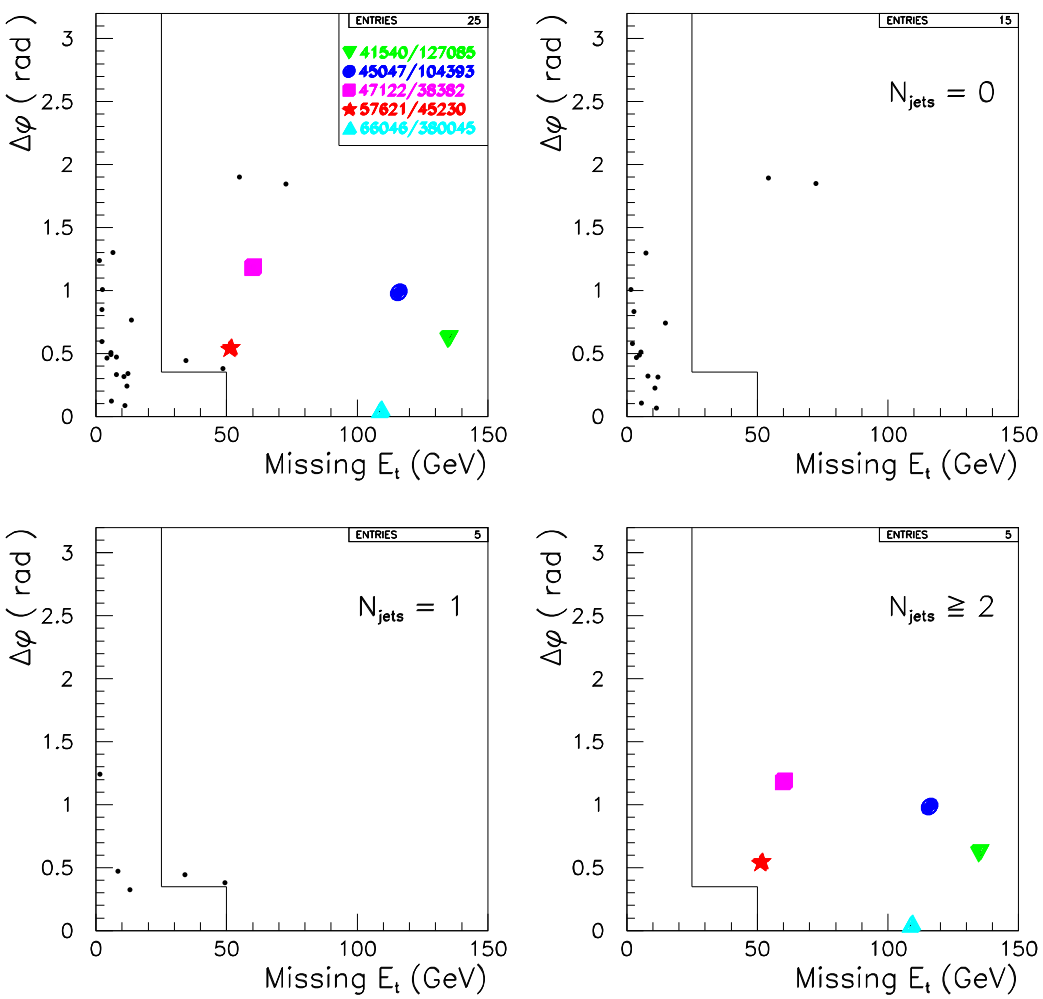


DiMuon Data for Run 1A and 1B



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 $t\bar{t}$

DØ Results for Dilepton Channel

DØ applies slightly different P_T cuts on leptons

- Goal is to optimise signal to noise
  - Lower lepton thresholds for $e\mu$ channel
  - Use H_T kinematic cut

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

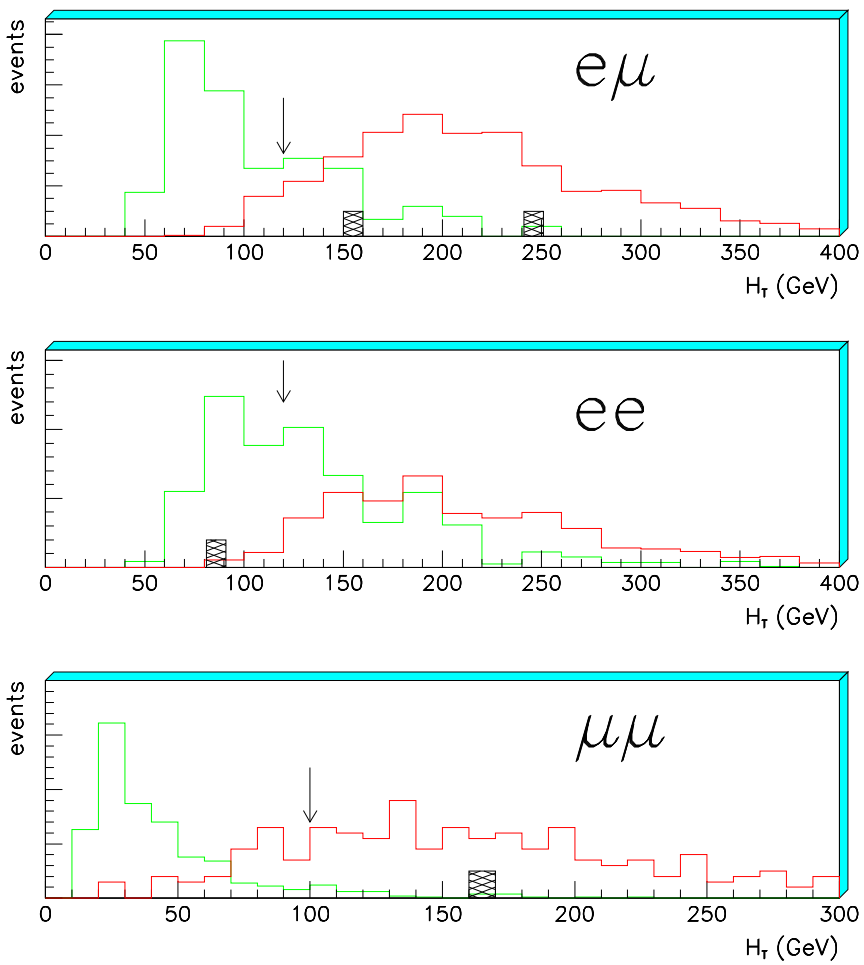
- Add electron E_T to H_T for ee and $e\mu$ channels
- ≥ 2 jets with $E_T > 15$ GeV and $|\eta| < 2.4$

	$e\mu$	ee	$\mu\mu$
Lepton P_T	$> 15/12$ GeV/c	> 20 GeV/c	> 15 GeV/c
$\not\!\!E_T$	> 20 GeV	> 25 GeV	
H_T	> 120 GeV	> 120 GeV	> 100 GeV

- Jet cuts are looser than for CDF
- Lepton thresholds are lower
- Use H_T cut to get comparable rejection

Data compared with expectation from

- Background modelled by Z production
- Signal is $t\bar{t}$ ISAJET MC
- Shaded are events that pass all other cuts



Results of DØ Dilepton Search

Background predicted to be Drell-Yan and $Z \rightarrow \tau^+\tau^-$.

	$e\mu$	e^+e^-	$\mu^+\mu^-$
$\int \mathcal{L}dt$ (pb^{-1})	48 ± 6	56 ± 7	44 ± 5
Data (events)	2	0	1
Backgrounds (events)	0.12 ± 0.03	0.28 ± 0.14	0.25 ± 0.04
$M_{top} = 140$ GeV/c^2	1.4	1.0	0.5
$M_{top} = 160$ GeV/c^2	0.9	0.7	0.4
$M_{top} = 180$ GeV/c^2	0.6	0.4	0.2

Observe 3 events and expect 0.65 ± 0.15 background

- Probability of background fluctuation is 0.03
- There is excess but not significant on its own

Summary of Dilepton Results

CDF/DØ observe **nine** events

- For CDF, results are very suggestive
  - Five electron and muon candidates
  - Three have b quark jet tags

- Expect a total of 2.0 ± 0.4 events background

Expected rate from top is small and depends on mass

M_{top} (GeV/c^2)	CDF events	DØ events
160	4.4	2.0
170	3.0	1.5
180	2.4	1.2

Statistically significant observations:

- Probability 1.3 events fluctuate to ≥ 6 events is 3.3×10^{-3}
- Probability 0.3 events fluctuate to ≥ 3 events is 3×10^{-2}

$\Rightarrow$ Have observed strong evidence for $t\bar{t}$

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

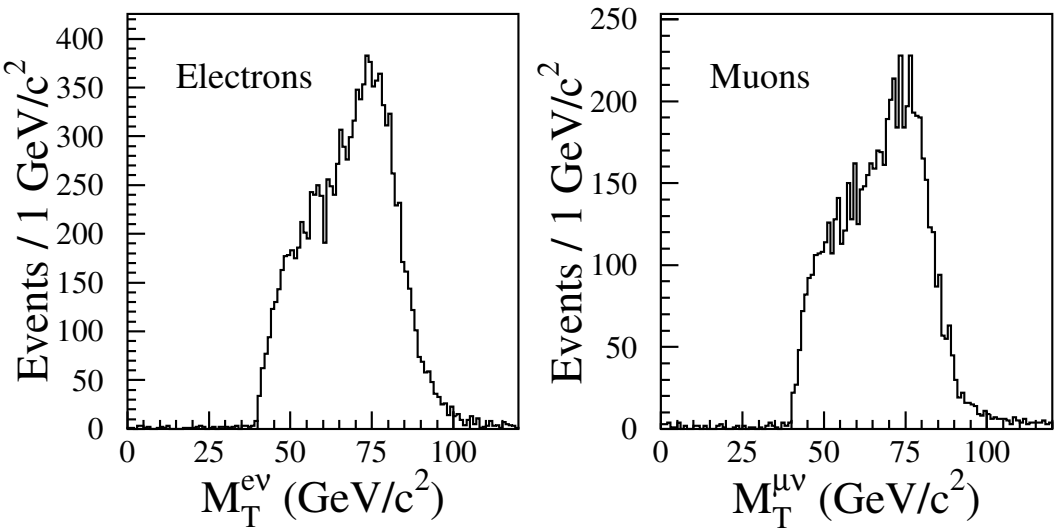
Selection of W candidates straightforward

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

Both experiments have large inclusive W samples

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

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



W + Jet Sample

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

- CDF: $\geq$ 3 jets with $E_T > 15$ GeV and $|\eta| < 2.0$
  - finds 203 W+$\geq$ 3 jet events
- DØ uses somewhat looser jet cuts
  - $E_T > 15$ GeV (corrected to parton E_T), $|\eta| < 2.4$
  - Places additional kinematic cuts

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

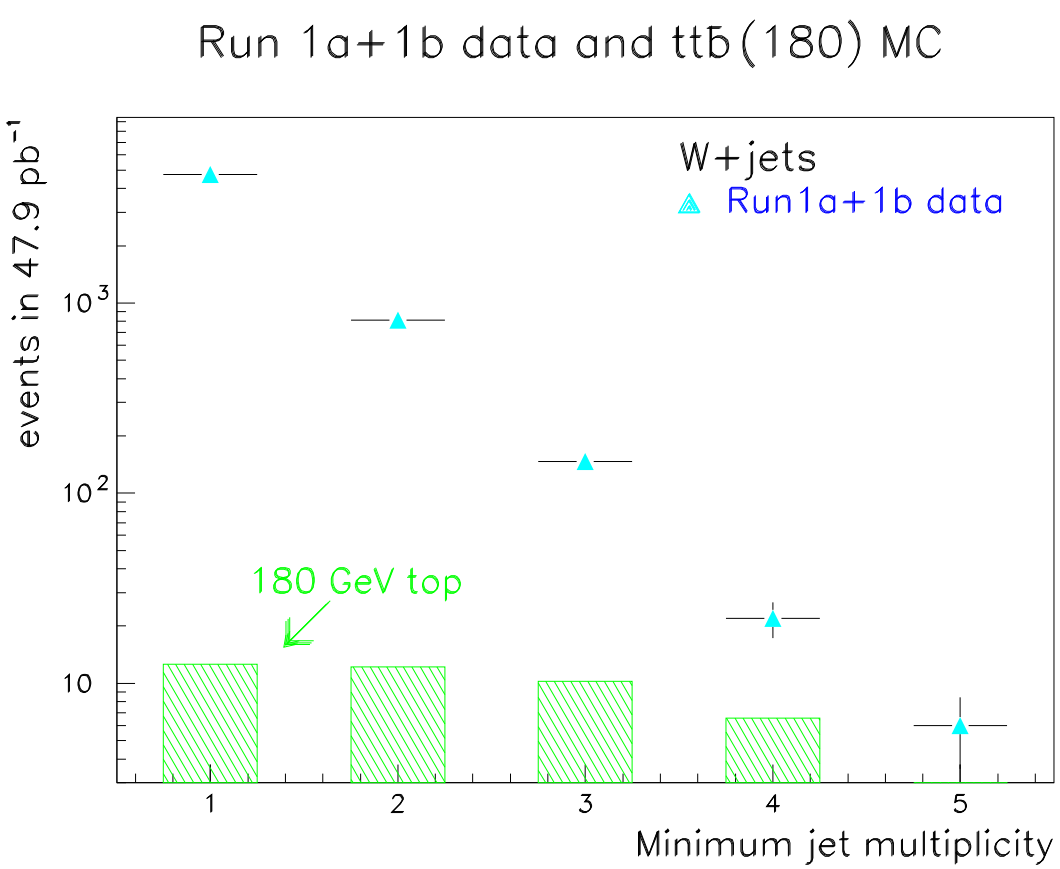
QCD W+jets production is largest expected background

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

The DØ data illustrates the serious S/N problem

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



Event Topology

Can use kinematics to separate $t\bar{t}$ from QCD background

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

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

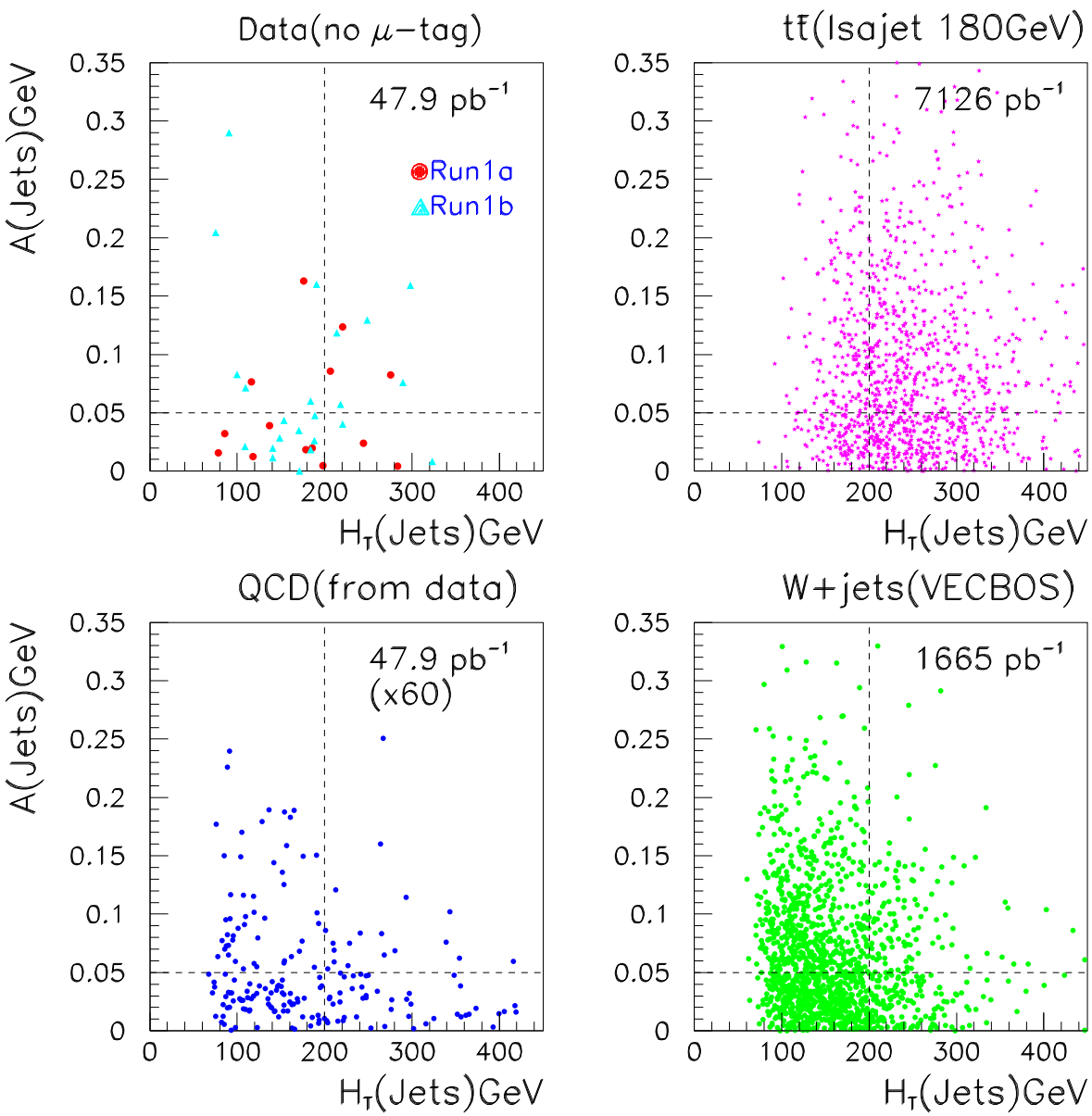
$\mathcal{A} \equiv \frac{3}{2} Q_1$ where Q_1 is smallest eigenvalue of M

- $t\bar{t}$ 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 $\mathcal{A} > 0.05$ and $H_T > 200$ GeV
- Estimate W+jet background by scaling jet multiplicities
- Observe 8 events and expect 1.9 ± 0.5 from background


Data(no μ−tag)
47.9 pb⁻¹
Run1a
Run1b
tt̄(Isajet 180GeV)
7126 pb⁻¹
QCD(from data)
47.9 pb⁻¹
(x60)
W+jets(VECBOS)
1665 pb⁻¹
A(Jets)GeV
H_T(Jets)GeV
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
100
200
300
400

W+jet Background Scaling

DØ estimates background in $W+ \geq 4$ jet sample

- assumes ratio $N(l+n \text{ jets})/N(l+(n-1)\text{jets})$ constant

  Berends et al., NP **B357**, 32 (1991).

- checked with Z+jets, W+jets ($n = 2, 3$)
- Determine N_{top} in $W+ \geq 4$ jet sample (w/o $\mathcal{A}, H_T$)
  - Apply $\mathcal{A}, H_T$ cuts, estimate effect on signal
  - Surviving background is 1.9 ± 0.5 events

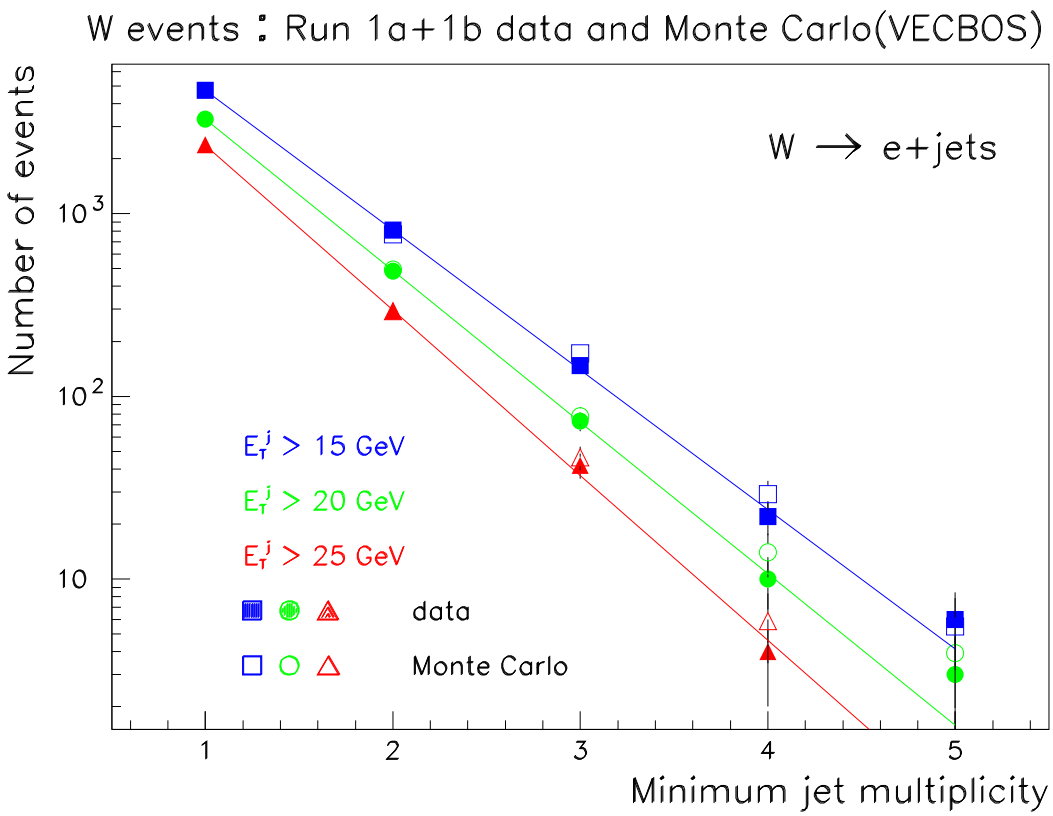
Need to know efficiency of $\mathcal{A}, H_T$ cuts on signal and background

- Checked by varying cuts
- Using Z+jets sample (statistically limited)

Jet Scaling Calculation (cont)

Indications are that scaling works well

- Have relatively small uncertainty on extrapolation



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)
   - CDF searches for both electrons and muons
   - DØ only uses soft muons
     - has higher efficiency for "cascade" decays

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

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

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

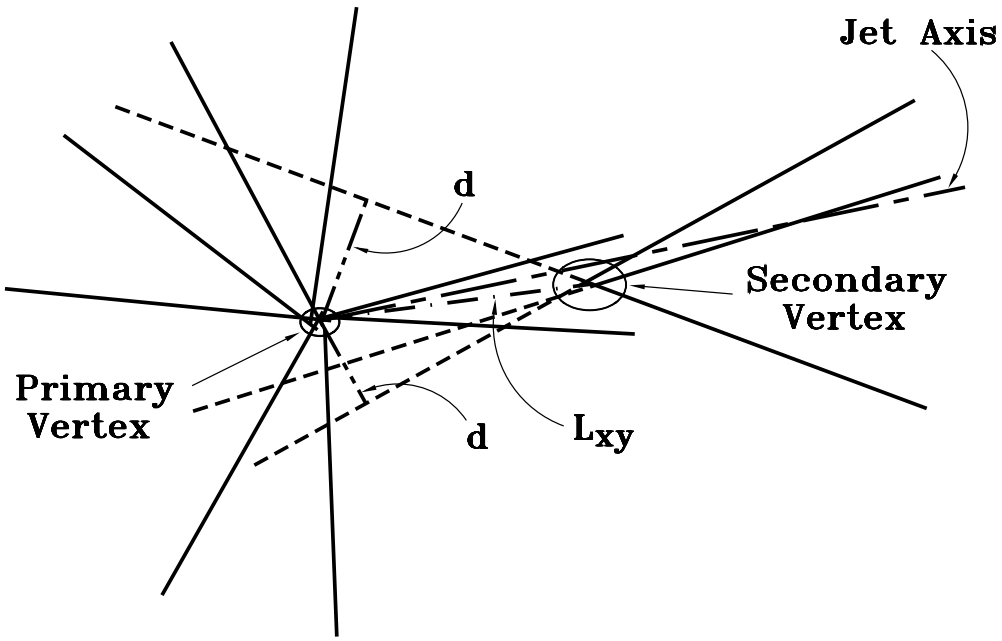
CDF has studied SLT tagging using

- photon conversions for electrons ($\gamma \rightarrow e^+e^-$)
- $J/\psi \rightarrow \mu^+\mu^-$ decays
- generic jets to obtain fake rates
  - fakes primarily hadron punch-through
  - "Fake" tagging rate is $\sim 0.005 - 0.010$ tags/track
- Efficiency is 0.152 ± 0.023 for $M_{top} = 160$ GeV/c^2

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



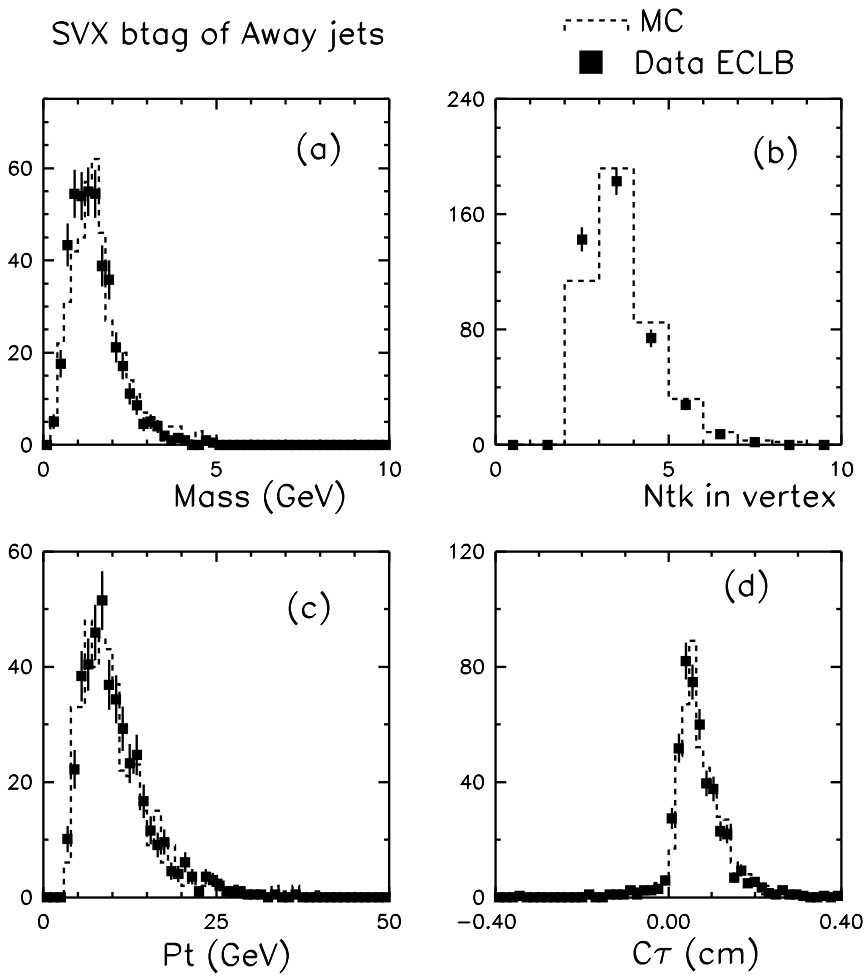
Used control samples to measure efficiency, fake rate

- 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