Top Physics at Hadron Colliders

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Lecture # 1

1. Introduction to Top Quark Physics
2. Production in Hadron Collisions
3. Top Decays and Detector Requirements
4. DØ and CDF Experiments
5. Multijet Decays
6. Dilepton Searches

Lecture # 2

1. Lepton + Jet Searches
2. B Quark Tagging
3. Results from Run 1A/1B
4. Cross section and mass estimates
5. Outlook & Conclusions

Lake Louise Winter Institute
February 1995

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

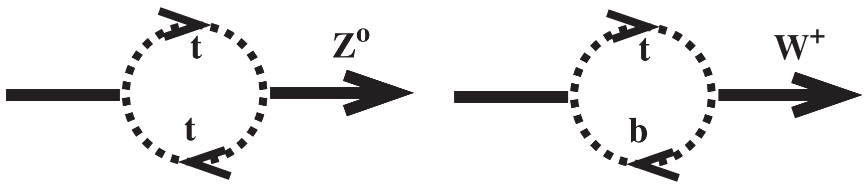
Electromagnetic force	γ
Strong force	eight gluons
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Gravity	gravitons

SM Predictions for Top Quarks

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

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

Corrections to $W^{\pm}$ and Z° masses depend on heaviests fermions



- LEP, SLD measurements on the Z resonance require

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

D. Schaile, CERN-PPE/94-162

Top Quark Phenomenology

Top Quarks decay via the weak force

- Predict 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^+

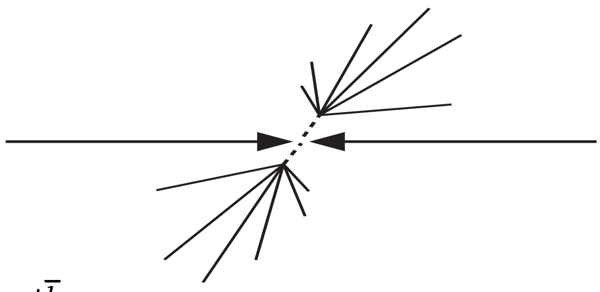
$$t \to H^+ b$$
$$\hookrightarrow \tau^+ \nu_\tau$$

- Top quark can be sensitive to SM details
  - V_{ts} CKM matrix elements
  - Constraints on other SM parameters (eg. A_{LR})

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

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).

Production of Top in Hadron Collisions

Top quark production is mediated by

$$q\bar{q}, gg \to t\bar{t}$$

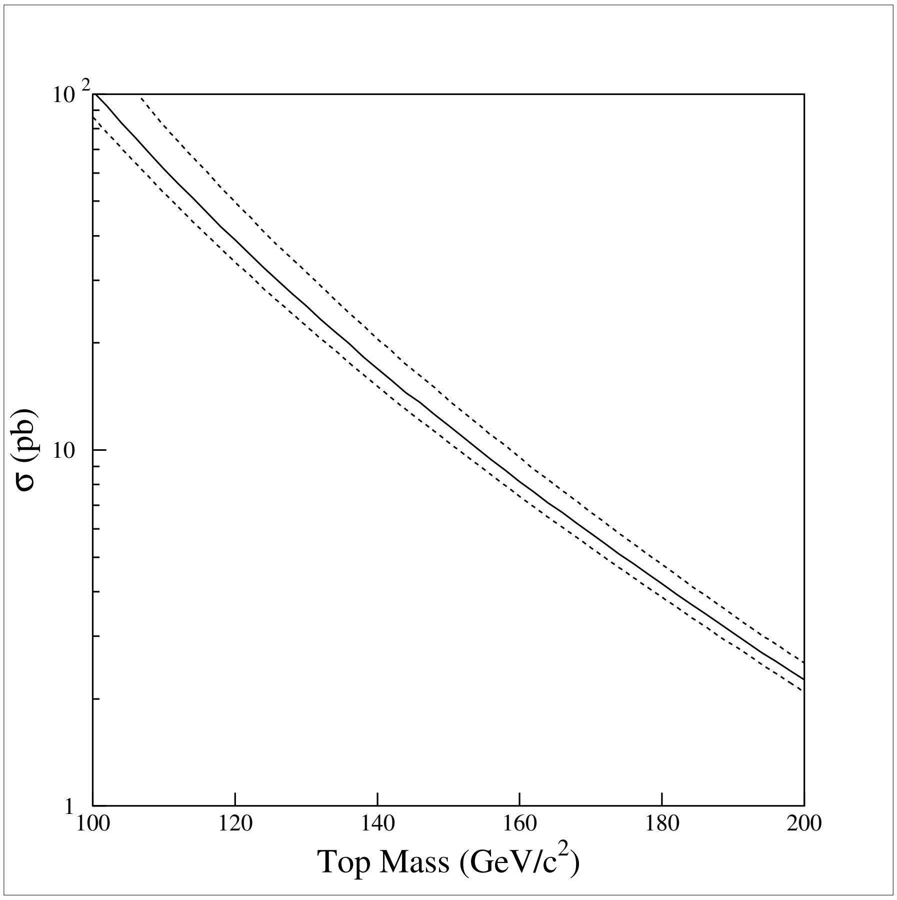
$$q\bar{q} \to t\bar{b}X$$

$$q\bar{q} \to W^{+} \to t\bar{b}$$

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



Top Decays and Detection Requirements

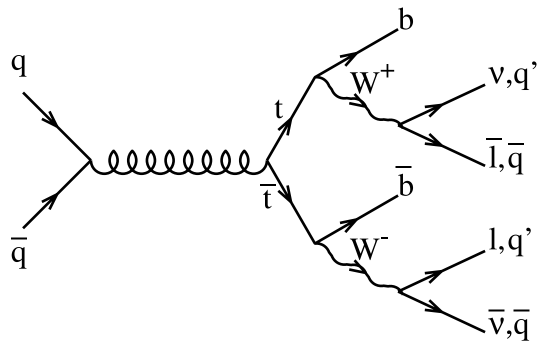
SM top quark decays via the weak force

$$t \rightarrow W^+ b$$

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

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

In proton-antiproton collisions,



This results in several distinct decay signatures

- Six jet final states
- Lepton + Jet events with at least one b quark
- Dilepton events with two, energetic $e^\pm$ and $\mu^\mp$
- Decay modes with τ's hard!

Detector Requirements

Detection of these decay modes requires

- Good jet reconstruction (energy and direction)
- Good lepton ID capability (acceptance and efficiency)
- Missing energy detection (for neutrinos)

Production/decay properties imply that

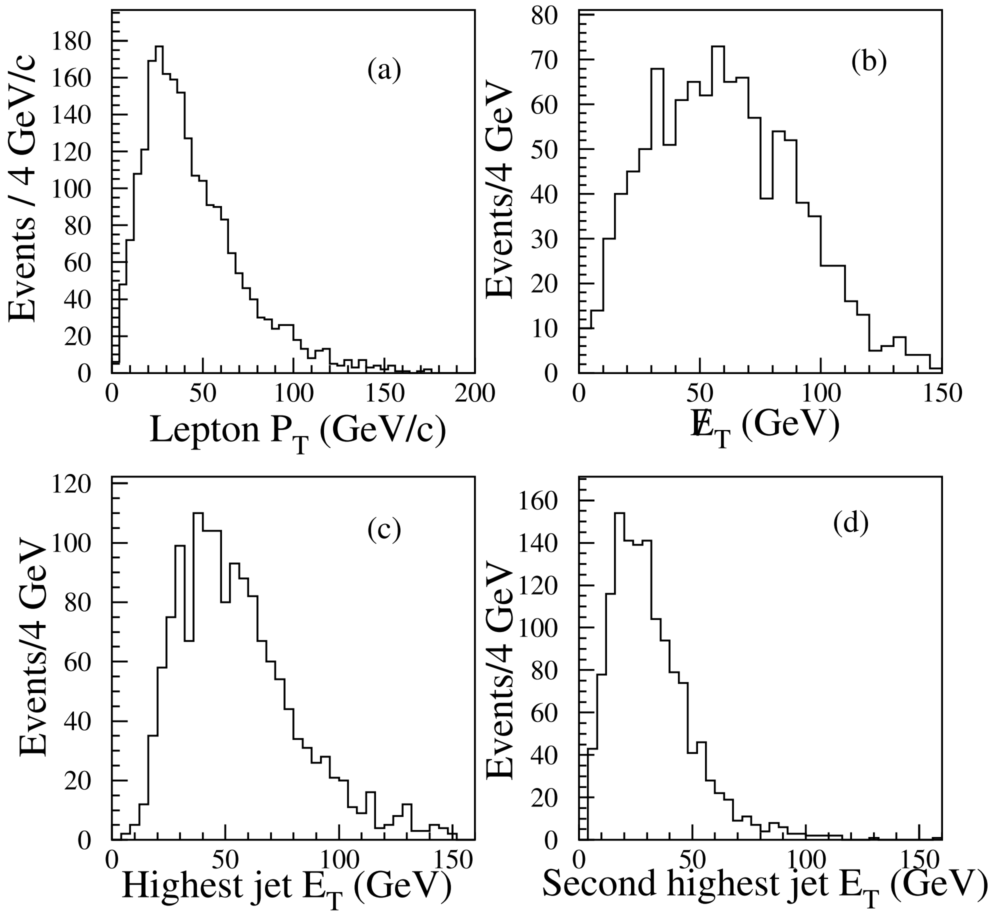
- Production is "central" (especially for high mass)
  - Most likely initial state is where $x_1 \sim x_2$
  - Top quarks are produced with modest P_T

    $\Rightarrow$ 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 with $M_{top} = 160$ in dilepton channel



$\boxed{\text{Background Considerations}}$

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
- Bottom line:

  $\boxed{\text{Background Studies Extremely Important}}$

$\boxed{\text{The Fermilab Collider Experiments}}$

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
  - 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 $|\eta| \lesssim 4$
  - Good hermiticity for $\not\!\!E_T$ measurement
  - Provides electron ID and jet detection

Detectors (continued)

- Muon chambers outside calorimeter
  - identify charge tracks that pass through calorimeter
  - DØ has toroidal magnets to measure muon P_T
- 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
  - 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

Both detectors have some 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
- Lack of magnetic field reduces redundancy
  - Calibration more difficult
  - Not able to detect secondary vertices

Triggering Issues

Detectors use 3-level trigger system to identify events in real-time

- Interaction rate of

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

  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 lepton(s)
- Missing energy requirements
- 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 $\sim$ 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 $\sim$ 55 pb^{-1}
  - DØ has updated results on top search (+22 pb^{-1})
  - CDF is currently preparing preliminary results
  - Run expected to continue till end of 1995
- Goal is to have in excess of 100 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 $\Rightarrow$ 160 produced $t\bar{t}$ events
  - expect to observe 1.3 dilepton events
  - expect to observe 3.5 lepton + jet events

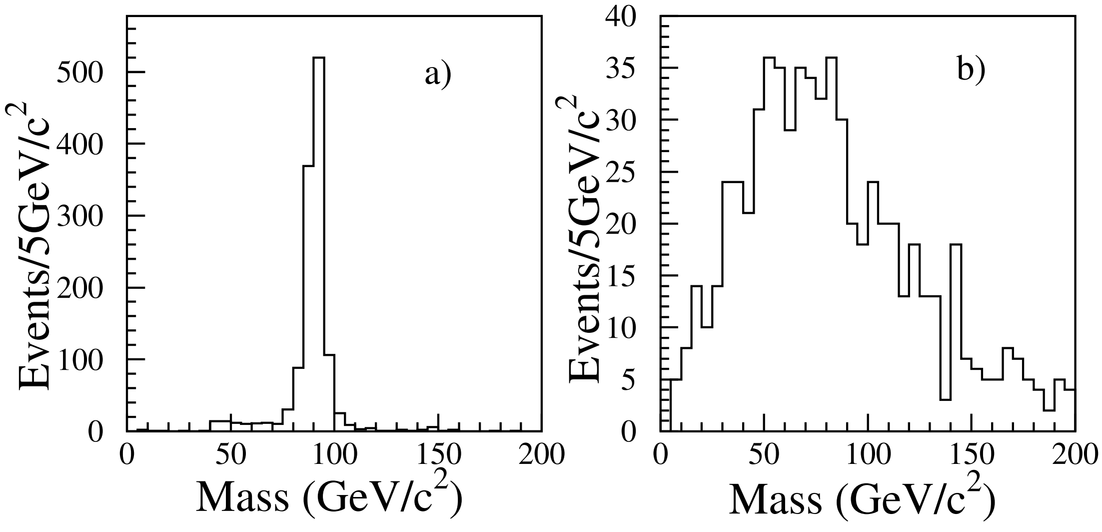
Dilepton Top Quark Search

$t\bar{t}$ 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

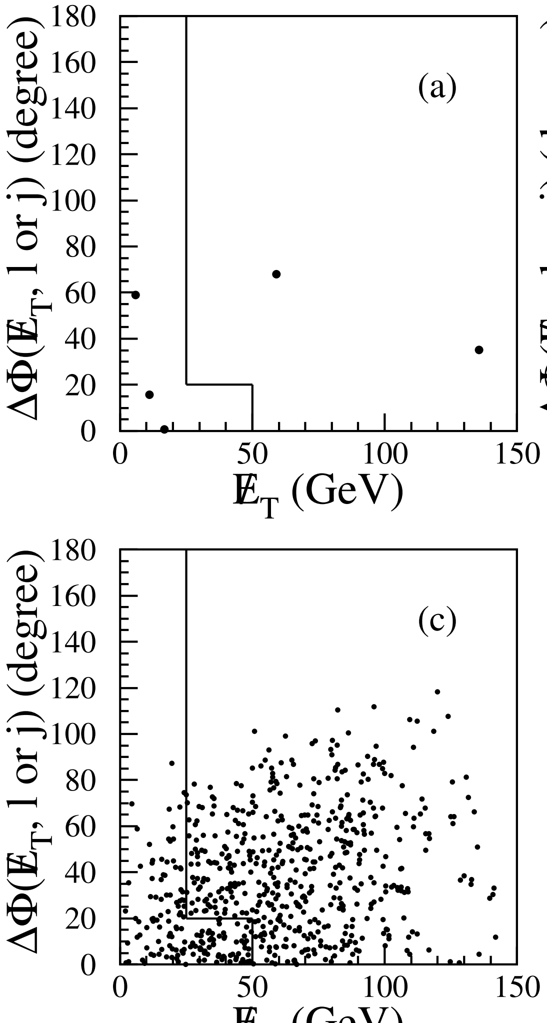
DØ and CDF performed a search requiring

- Two clean, high P_T lepton candidates
- Missing transverse energy $\not{E}_T > 25$ GeV
- Require two jets with E_T> 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



CDF Results for Dilepton Channel

Have measured the rate of events from non-top sources

- Have used data to measure these rates
- Cross-checked using $Z^\circ \rightarrow e^+e^-$ and $Z^\circ \rightarrow \mu^+\mu^-$
- Consistent with theoretical calculations

Background	**e**μ	**ee**, $\mu\mu$
$Z \rightarrow \tau^+\tau^-$	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	$0.31^{+0.24}_{-0.10}$

CDF observes 2 $e\mu$ events

- Expect $0.56^{+0.25}_{-0.13}$ background events

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
- Jet cuts reject larger background fraction

They observe two events in their 1A and 1B data

	$e\mu$	e^+e^-	$\mu^+\mu^-$
Data (1A)	1	0	0
Data (1B)	1	0	0
Backgrounds	0.7 ± 0.1	0.5 ± 0.1	0.8 ± 0.1
$M_{top} = 140$ GeV/c^2	2.3	1.2	0.6
$M_{top} = 160$ GeV/c^2	1.2	0.7	0.3
$M_{top} = 180$ GeV/c^2	0.7	0.4	0.1

Observe 2 events and expect 2.0 ± 0.2 background

- Not very sensitive to top

Summary of Dilepton Results

CDF/DØ observe **four** $e\mu$ events

- For CDF, result appears more significant
  - Both events have electron and muon candidates
  - One has signature of b quark jet

- For DØ, observation consistent with background

Expected rate from top is small and depends on mass

M_{top} (GeV/c^2)	CDF events	DØ events
140	2.2	3.5
160	1.3	1.9
180	0.7	1.1

Overall significance is low

- Probability 0.56 events fluctuate to ≥ 2 events is 12%

- DØ result totally consistent with background

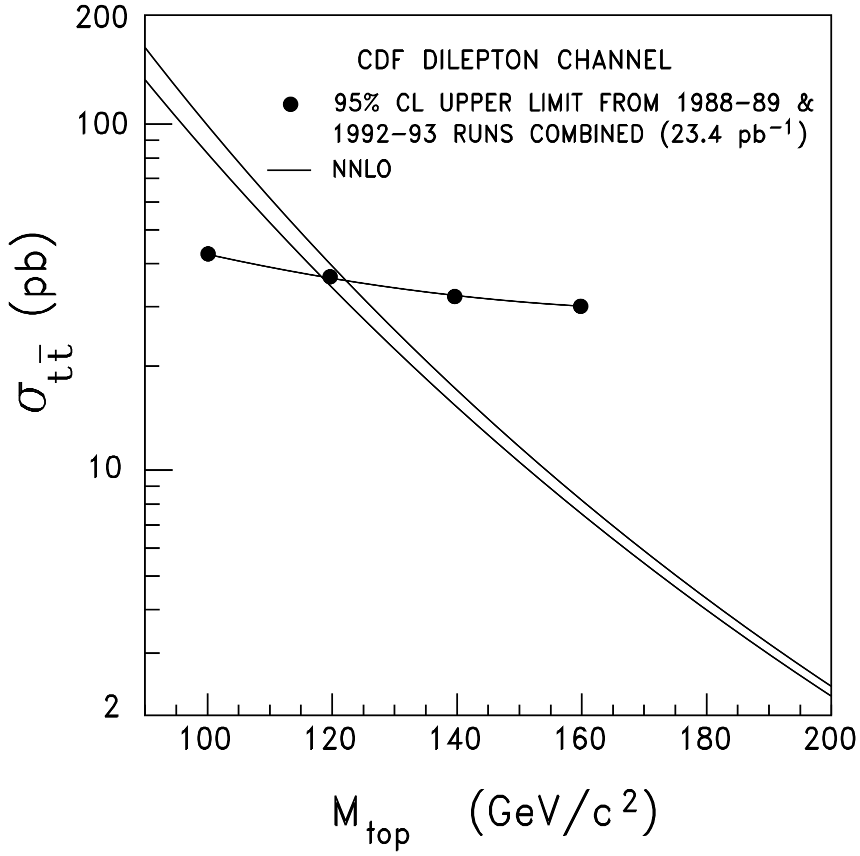
  $\Rightarrow$ Not statistically significant

Mass Limits from Dilepton Data

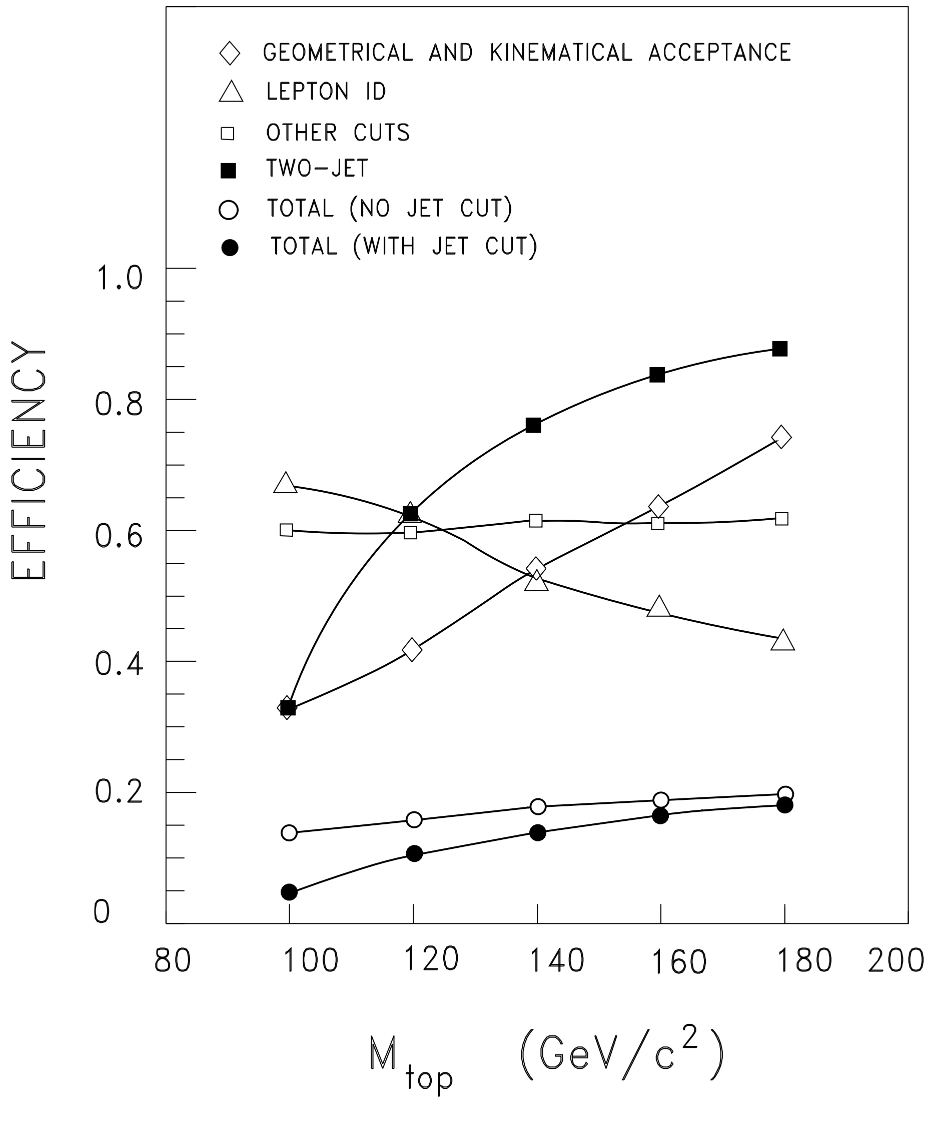
CDF uses dilepton data to exclude "low mass" top

- In this case, CDF removes 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}

DØ has chosen not to update its lower mass limit



Dilepton acceptance as a function of top mass



$\boxed{\textbf{So What About Multijets?}}$

$t\bar{t} \rightarrow 6j$ faces huge QCD multijet background

- QCD cross section is over 4 orders of magnitude larger
- Have been some studies
  - Can use kinematic cuts to get of order 10^3 rejection
  - Use b quark tagging techniques to get $\times 10$
- Still left with signal-to-background of 1-10 to 1-50!

$\Rightarrow$ most people have given up!