Top Physics at the Tevatron

Jim Cochran
University of California, Riverside
For the DØ and CDF Collaborations

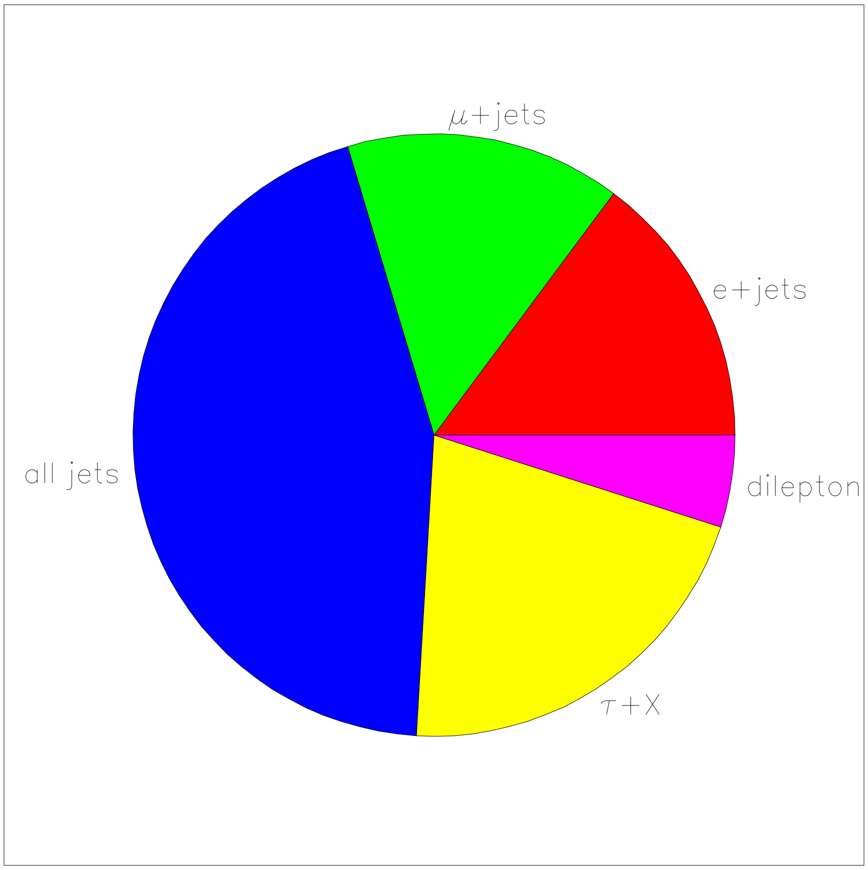
Physics in Collision '97
University of Bristol
June 26, 1997

Outline

- Top production and overview
- Cross section measurements
- Mass measurements
- Kinematic Properties of the $t\bar{t}$ system
- Summary

Top Production and Decay

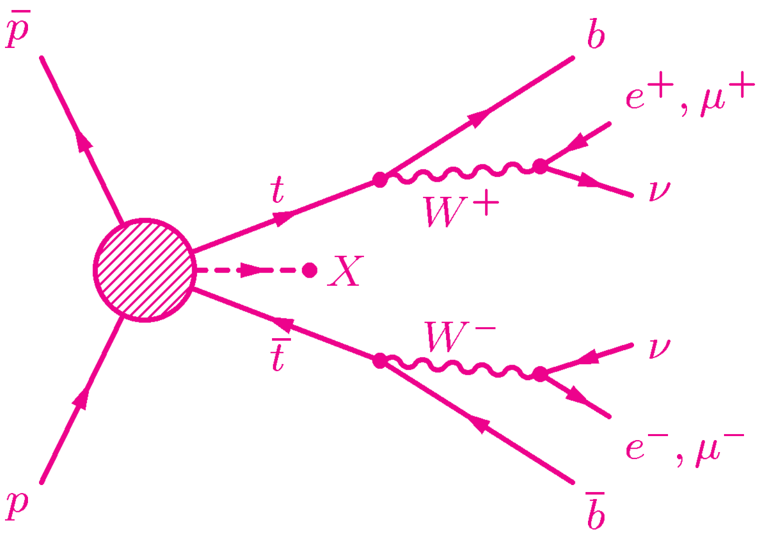
- At the Tevatron, top quarks are produced primarily in pairs via $q\bar{q} \rightarrow t\bar{t}(\sim 90\%)$ and $gg \rightarrow t\bar{t}(\sim 10\%)$
- Assuming standard model couplings,
  - BR$(t \rightarrow Wb) = 100$ %
  - catagorize channels by W Decay mode



Cross Section Measurements

- Dilepton channels
  - $ee, e\mu, \mu\mu$ channels
  - $e\nu$ channel
  - $e\tau$ and $\mu\tau$ channels
- Lepton+jets channels
  - topological tagging
  - secondary vertex b-tagging
  - soft lepton b-tagging
- All jets channels

Dilepton Channels



- Signal Characteristics
  - 2 isolated, oppositely charged, high-p_T leptons
  - significant $\not{E}_T$
  - 2 jets from b quarks
- Branching Ratio: ~5 % $(e\mu + ee + \mu\mu)$
- Backgrounds
  - Drell-Yan production, $Z \to \ell\ell$
  - WW, $Z \to \tau\tau$
  - QCD: $b\bar{b}, c\bar{c} \to \ell\ell$
  - Jets misidentified as electrons
- Good S/B, limited statistics

Dilepton Analyses

Event Selection

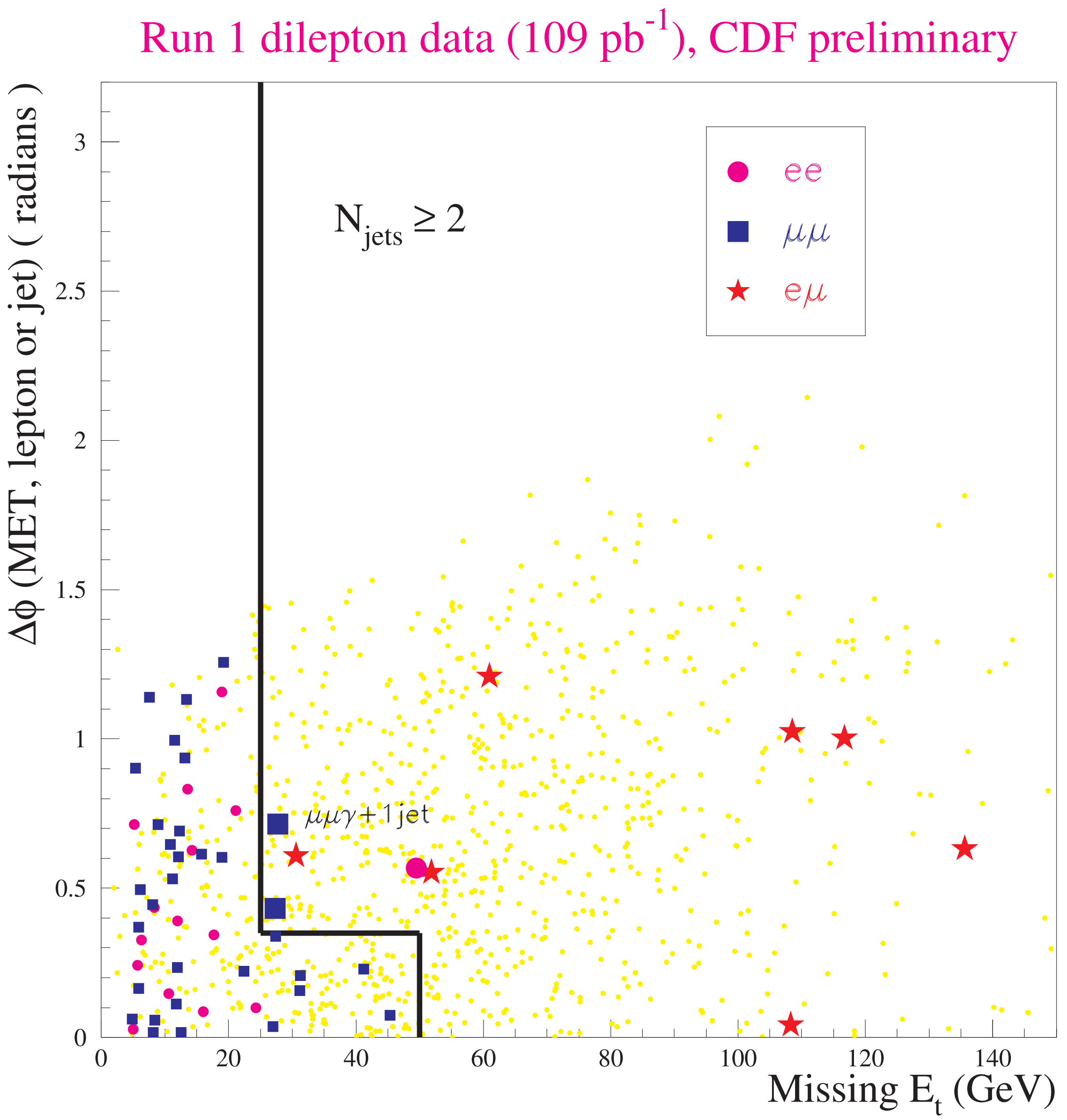
Cut	DØ	CDF
$N(\ell)$	2	2
$p_T^\ell \geq$	15, 20 (ee)	20
$\|\eta\|_\ell \leq$	2.5(e), 1.7(μ)	1.05
$\not{E}_T \geq$	20$(e\mu)$, 25(ee)	25,50 if $\Delta\Phi < 20^\circ$
$N(j) \geq$	2	2
$E_T^j \geq$	20	10
$\|\eta\|_j \leq$	2.5	2.0
$\|M_{\ell\ell} - M_Z\| \geq$	12 if $\not{E}_T < 40, \mu\mu \neq Z$	15
$H_T^e \geq$	120$(ee, e\mu)$	-
$H_T \geq$	100$(\mu\mu)$	-

$\ell = e$ or μ
Energies, masses, and momenta are in GeV, GeV/c^2, and GeV/c

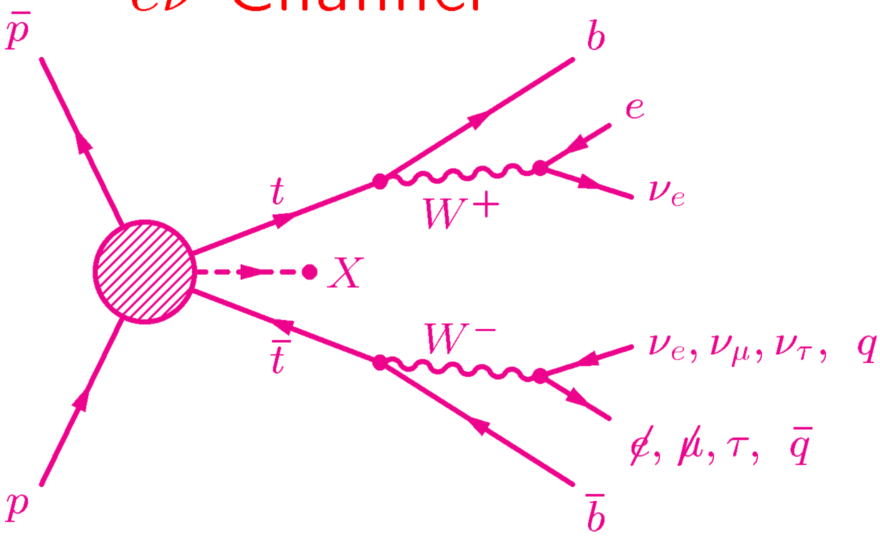
Results

	DØ	CDF
Data Events	5	9
Expected Background	1.4 ± 0.4	2.1 ± 0.4
Expected Top	4.1 ± 0.7 at 170 GeV/c^2	6.3 ± 0.6 at 7.5 pb
Cross Section	5.0 ± 3.3 pb at 173 GeV/c^2	$8.5^{+4.4}_{-3.4}$ pb at 175 GeV/c^2

CDF Dilepton Events



$e\nu$ Channel

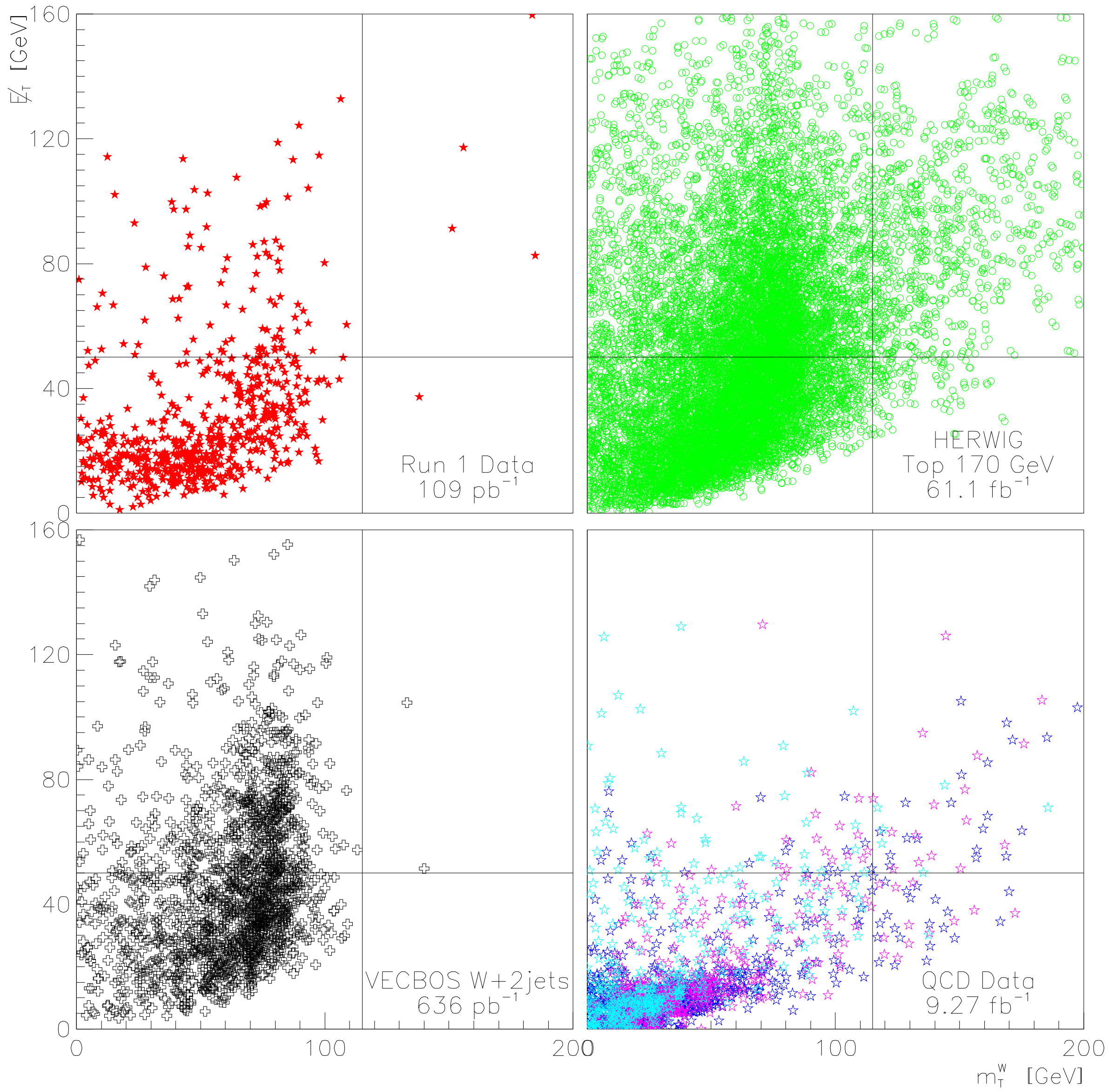


- Signal Characteristics
  - Isolated, high-p_T electron
  - significant $\not{E}_T$
  - Large $M_T(e, \not{E}_T)$
  - 2 jets from b quarks

- Backgrounds
  - W+jets
  - multijet events with a jet misidentified as an e
  - WW, WZ

- Mixture of events from $\ell\ell$ and e+jets channels, which fail the standard selections for these channels (50% $e\mu + ee$, 33% e + jets, 17% $e\tau$)

$e\nu$ channel (DØ): $\not\!\!E_T$ vs $M_T(e, \not\!\!E_T)$



$e\nu$ channel (DØ)

Event Selection

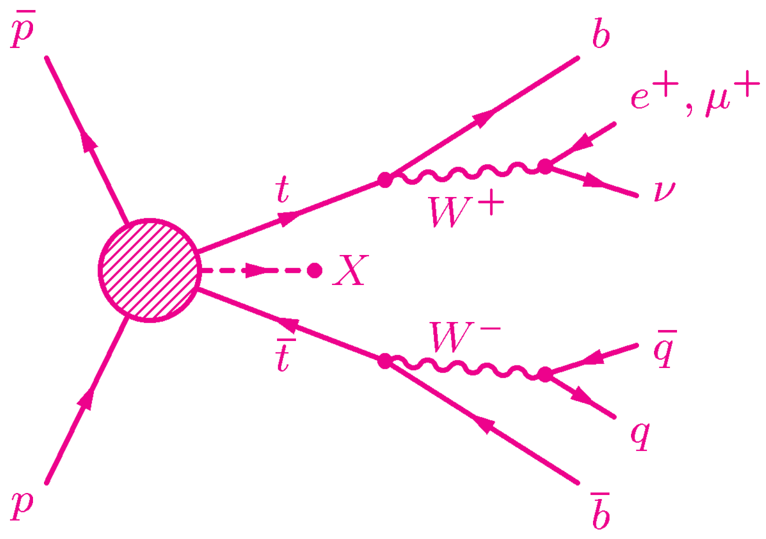
Lepton	$E_T(e) \geq 20$ GeV, $\lvert\eta_e\rvert \leq 1.1$
$\not{E}_T$	$\not{E}_T \geq 50$ GeV
reject multijet with fake e	$\Delta\phi(\not{E}_T, E_T^{\text{jet2}}) \geq 0.5$ rad
Jets	2 jets, $E_T \geq 30$ GeV $\lvert\eta_j\rvert \leq 2.0$
Orthogonality	reject ee, $e\mu$, e+jets, and e+jets/μ

Results for Run I (108 pb^{-1})

Events Observed	4
Expected Background	1.2 ± 0.4
Expected Top ($m_t = 170$ GeV/c^2)	1.7 ± 0.5

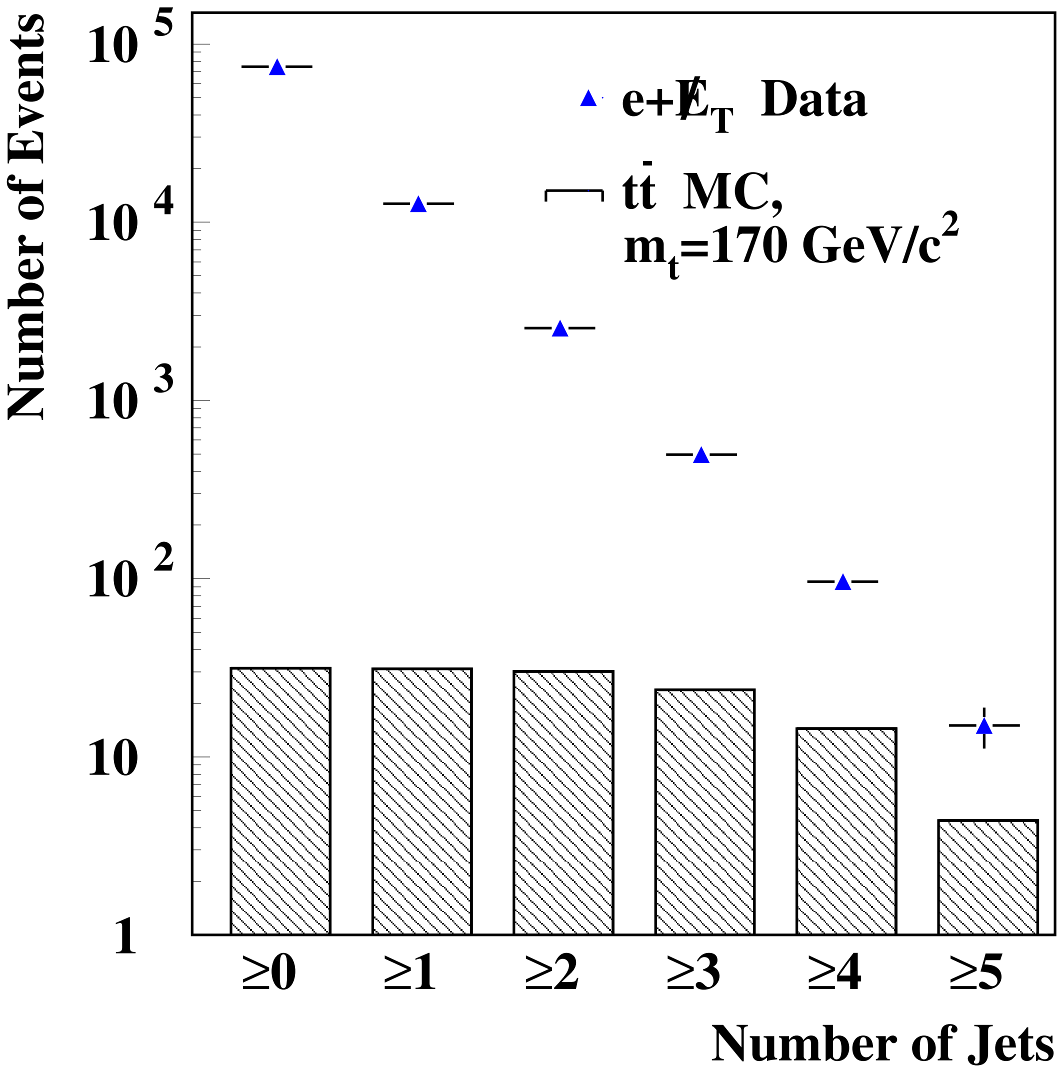
$\sigma_{t\bar{t}} = 9.3 \pm 7.3$ pb
(at $m_t = 173.3$ GeV/c^2)

Lepton + jets Channels



- Signal Characteristics
  - One isolated, high-p_T lepton
  - $\not{E}_T$
  - 4 or more jets (2 from b quarks)
- Branching ratio: ∼15% per lepton flavor
- Dominant backgrounds
  - W+jets production
  - multijet events with a jet misidentified as an e

Jet multiplicity



0 1 2 3 4 5

Cutting on lepton p_T, $\not{E}_T$, and jet E_T, is a good start, but the background still dominates.

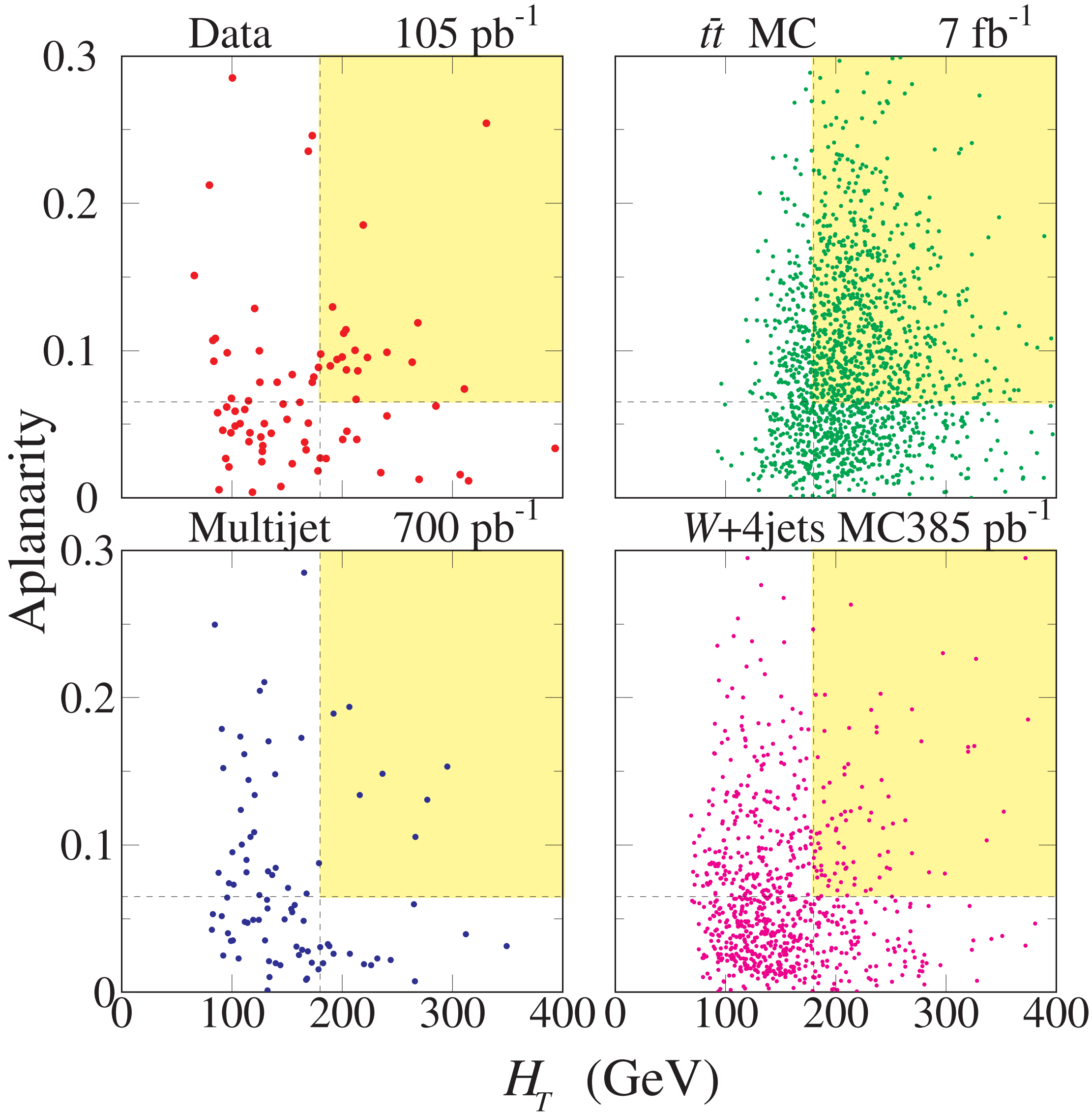
The are 2 primary techniques:

- Topological Tagging (DØ)
  - Total leptonic E_T: $E_T^L \equiv E_T^\ell + \not{E}_T$
    Large E_T^L suppresses instrumental background
  - Hadronic Activity: $H_T \equiv \Sigma E_T^{\text{jet}}$
    Large H_T signifies the decay of a massive object
  - Aplanarity A:
    $M^{ab} = \Sigma p^a p^b / \Sigma p^2$ (momentum tensor for W +jets)
    $A \equiv 3/2$ x (smallest eigenvalue)
    $A = 1/2$ for spherical events, 0 for planar events

    $t\bar{t}$ events are expected to be more spherical than events arising from radiative QCD processes

- b-jet tagging
  - displaced vertex of $b \to X$ (CDF)
    $\epsilon = 41 \pm 4\%$
    Typical fake rate per jet = 0.5%
  - low p_T lepton from semileptonic b decay (CDF and DØ)
    $\epsilon = 20 \pm 2\%$
    Typical fake rate per jet = 2%

ℓ+jets channel (DØ): A vs H_T



A and H_T cuts are optimized to minimize the fractional cross section error, $\Delta\sigma/\sigma$, at selected S/B

ℓ+jets Topological Analysis (DØ)

Event Selection

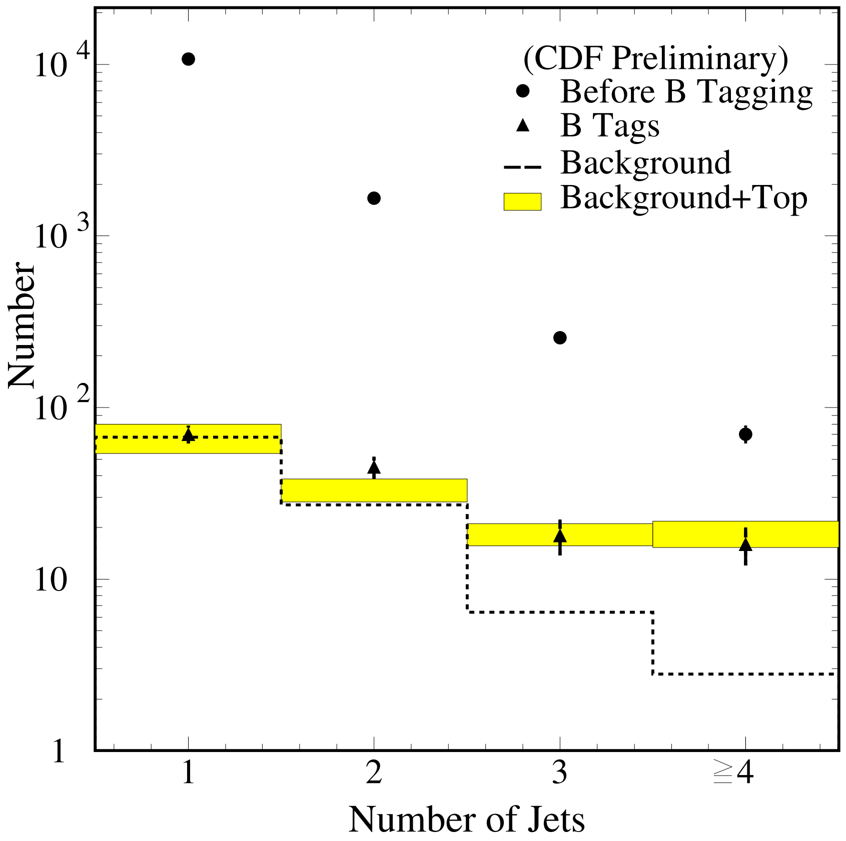
	e+jets	μ+jets
Lepton	$E_T(e) \geq 20$ GeV $\lvert\eta_e\rvert \leq 2.0$	$p_T(\mu) \geq 20$ GeV/c $\lvert\eta_\mu\rvert \leq 1.7$
$\not\!\!E_T$	$\not\!\!E_T \geq 25$ GeV	$\not\!\!E_T \geq 20$ GeV
Jets	≥ 4 jets, $E_T^j \geq 15$ GeV, $\lvert\eta_j\rvert \leq 2.0$	
Shape Cuts	$E_T^L \geq 60$ GeV $H_T \geq 180$ GeV $A \geq 0.065$	
	$\lvert\eta_W\rvert \leq 2.0$	
	veto μ tag events	

Results for Run I (110 pb^{-1})

Events Observed	19
Expected Background	8.7 ± 1.7
Expected Top ($m_t = 170$ GeV/c^2)	14.1 ± 3.1

$\sigma_{t\bar{t}} = 4.1 \pm 2.0$ pb
(at $m_t = 173.3$ GeV/c^2)

ℓ+jets channel (CDF): SVX b-tag results



Results for Run I (109 pb^{-1})

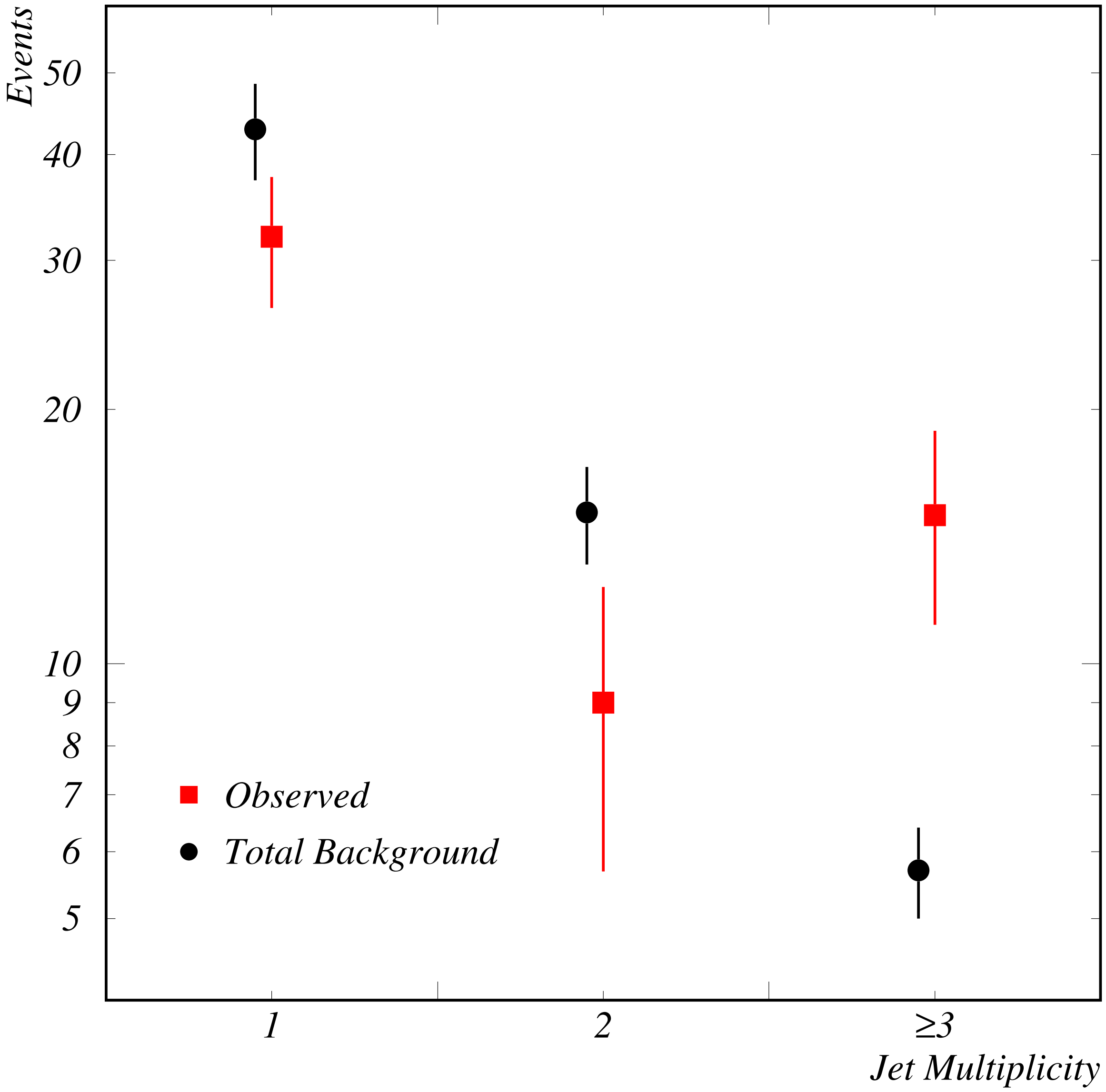
Events Observed	34 (44 tagged jets)
Expected Background	8.0 ± 1.4
Expected Top ($\sigma_{t\bar{t}} = 7.5$ pb)	31.0 ± 7.5

$$\sigma_{t\bar{t}} = 6.8^{+2.3}_{-1.8} \text{ pb}$$

(at $m_t = 175$ GeV/c^2)

ℓ+jets+μ-tag channel (DØ)
Jet Multiplicity

Before applying event shape (A, H_T) cuts



ℓ+jets+soft-lepton-tag Analyses

Event Selection

Cut	DØ	CDF
$N(\ell)$	1	1
$p_T^\ell \geq$	20	20
$\vert\eta\vert_\ell \leq$	2.0(e), 1.7(μ)	1.05
$\not{E}_T \geq$	20	20
$N(j) \geq$	3	3
$E_T^j \geq$	20	15
$\vert\eta\vert_j \leq$	2.0	2.0
Shape	$H_T \geq 110, A \geq 0.04$	-
Soft Lepton tag	$p_T^\mu \geq 4, \Delta R(\mu, j) \leq 0.5$	SLT

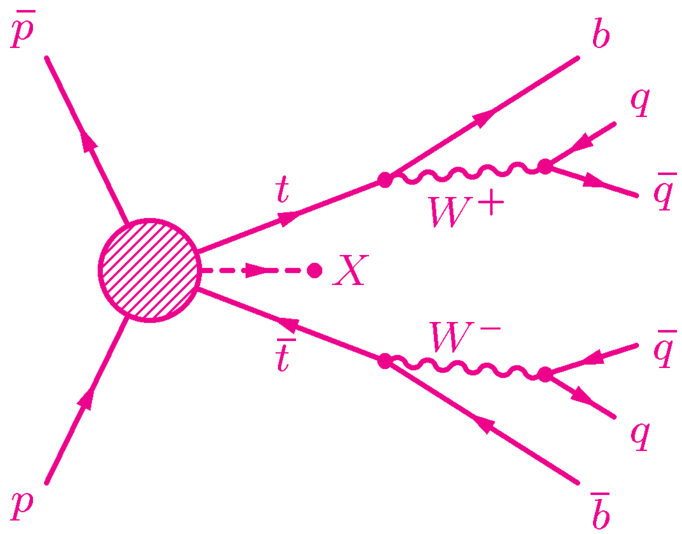
$\ell = e$ or μ

Energies, masses, and momenta are in GeV, GeV/c^2, and GeV/c

Results

	DØ	CDF
Data Events	11	40
Expected Background	2.4 ± 0.5	24.3 ± 3.5
Expected Top	5.8 ± 1.0 at 170 GeV/c^2	15.2 ± 3.8 at 7.5 pb
Cross Section	8.2 ± 3.5 pb at 173 GeV/c^2	$8.0^{+4.4}_{-3.6}$ pb at 175 GeV/c^2

All jets Channels



- Signal Characteristics
  - 6 or more jets (2 from b quarks)
  - large $H_T(\equiv \Sigma E_T^{\text{jets}})$
- Branching Ratio: $\sim$44%
- Dominant Backgrounds
  - QCD multijet events
- Features:
  - Not all 6 jets are always observed
  - Very low S/B ($\sim$1/500) before additional topological/kinematic or b-tagging requirements

CDF Alljets
1 displaced vertex tag + topological analysis

- Begin with a sample of ~230,000 events with at least 4 jets with $E_T \geq 15$ GeV and $|\eta| \leq 2$: S/B = 1/500

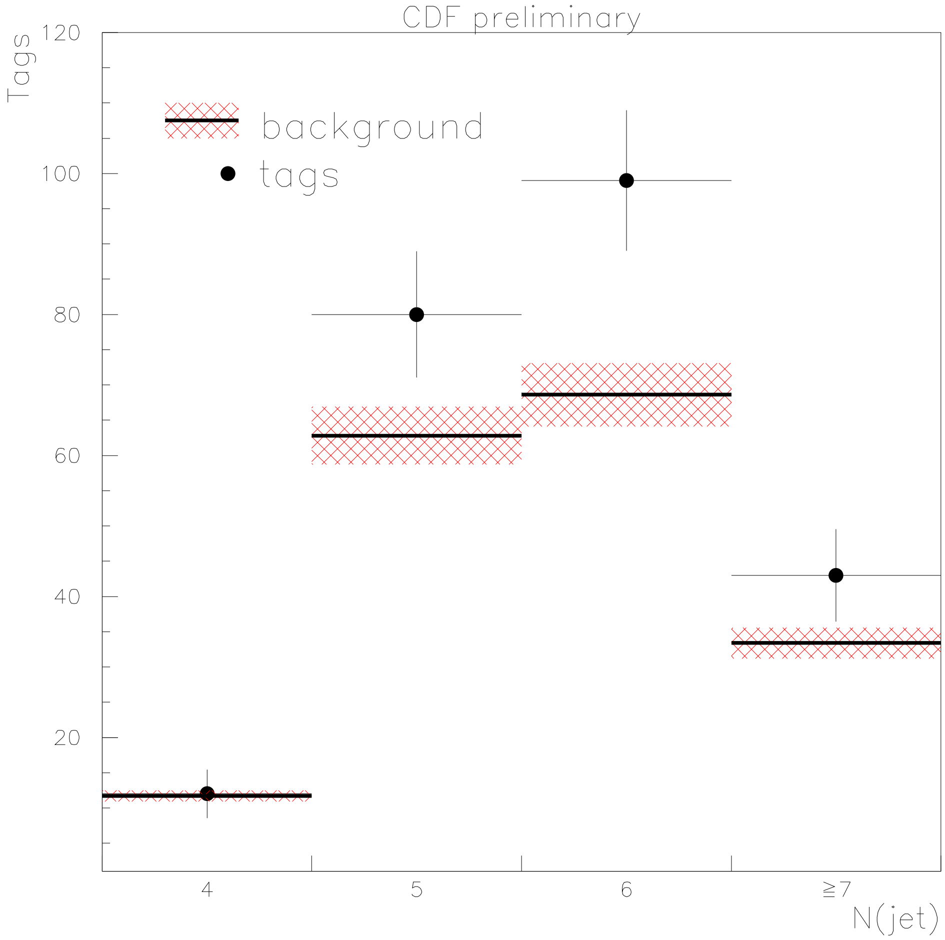
- Further selection
  - 5 $\leq$ N(jets) $\leq$ 8
  - ΔR(jet, jet) $\geq$ 0.5
  - ΣE_T(jets) $\geq$ 300 GeV
  - Energy centrally deposited: $\Sigma E_T(\text{jets})/\sqrt{s} \geq 0.75$
  - N-2 subleading jets sufficiently aplanar: $A + 0.0025\Sigma E_T^j \geq 3 \geq 0.54$

  1621 events

- Finally displaced tag requirement ($\epsilon = 47 \pm 5\%$) yields:

187 tagged events
142 ± 12 background

CDF Alljets
1 displaced vertex tag + topological results



$$\sigma_{t\bar{t}} = 9.6^{+4.4}_{-3.6}\ \text{pb}$$
(at $m_t = 175\ \text{GeV}/c^2$)

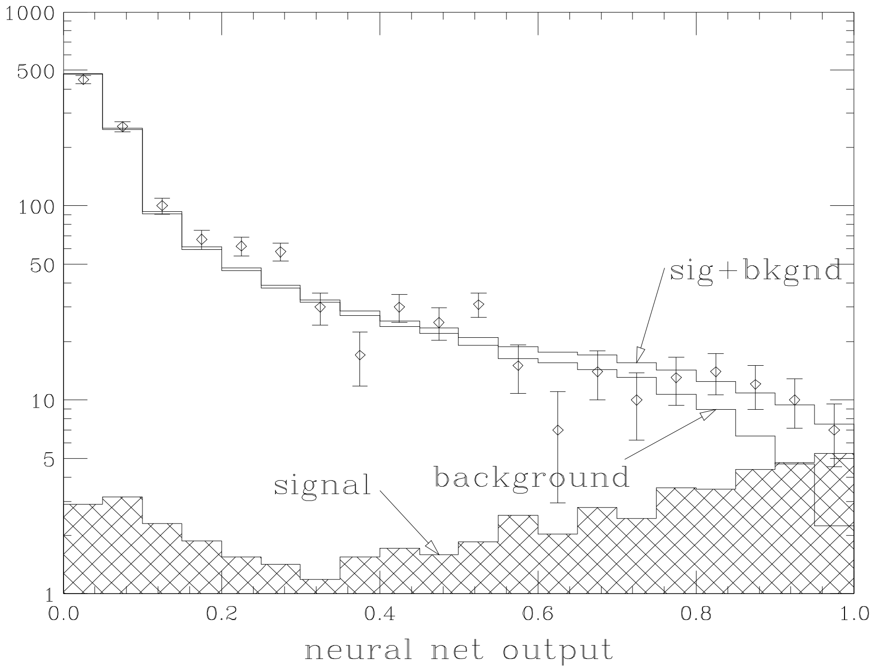
Fermilab-Pub-97/075-E, submitted to PRL

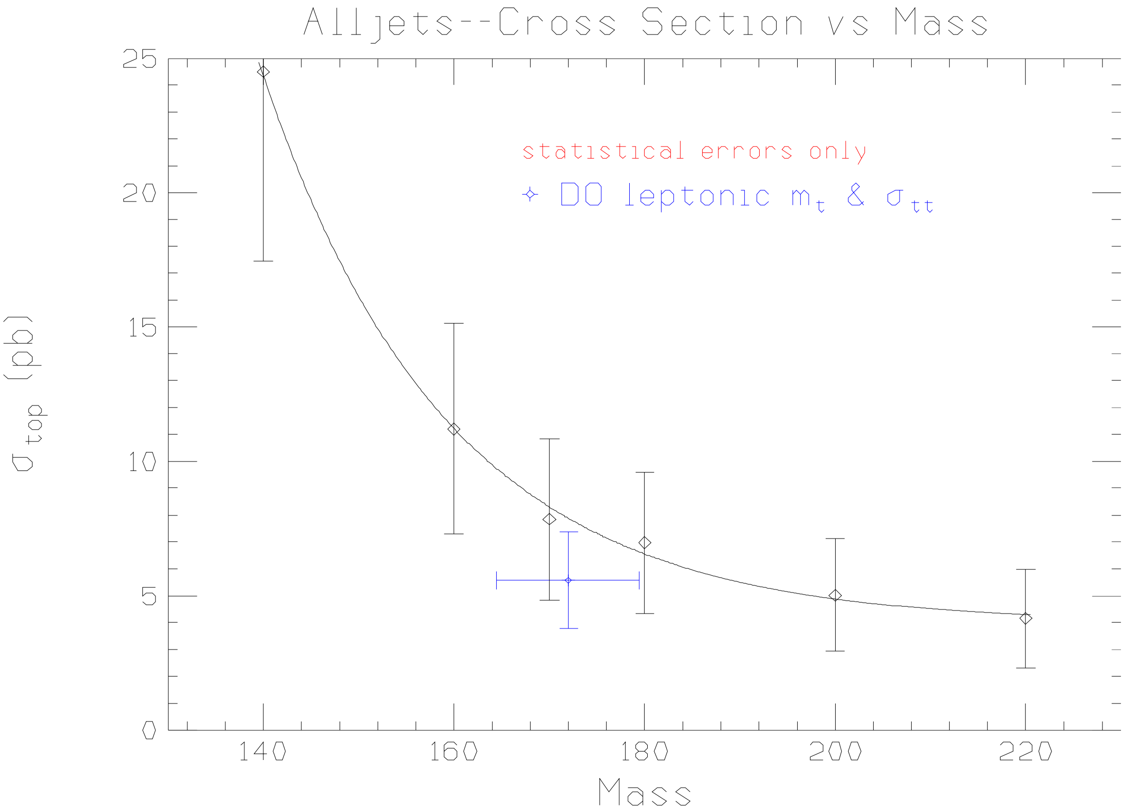
DØ Alljets analysis

Basi

• net-

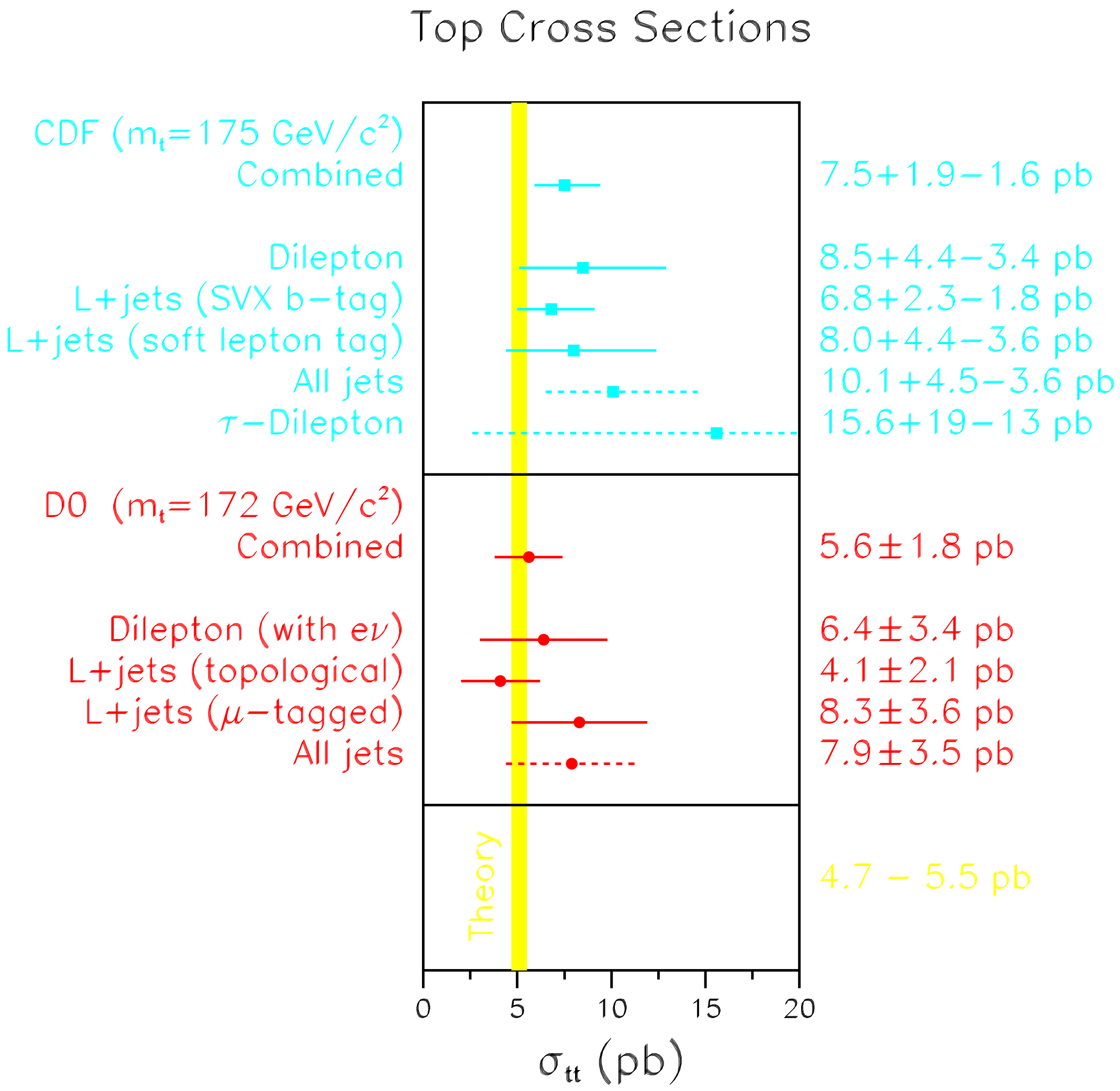
ality,





Alljets--Cross Section vs Mass
statistical errors only
D0 leptonic m_t & σ_{tt}
σ_{top} (pb)
Mass
0
5
10
15
20
25
140
160
180
200
220

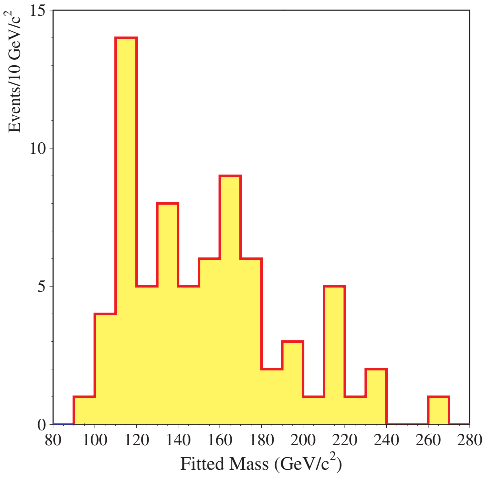
Summary of $\sigma_{t\bar{t}}$ measurements



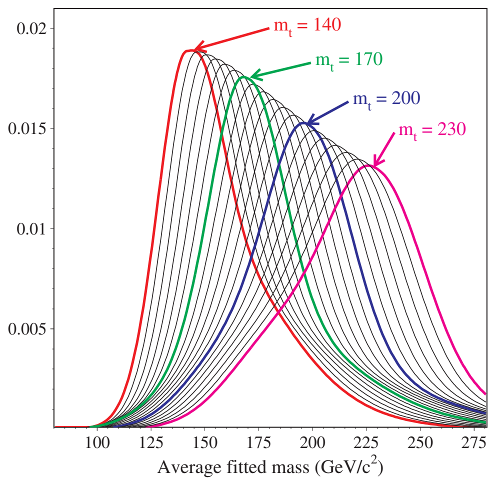
Mass Measurements

- How to measure the top mass
- Lepton + jets measurements
- Dilepton measurements
- All-jets measurement
- Summary

Select a sample of top candidates
For each candidate make a measurement of $X = f(m_t)$
Now one has a distribution from which to extract m_t



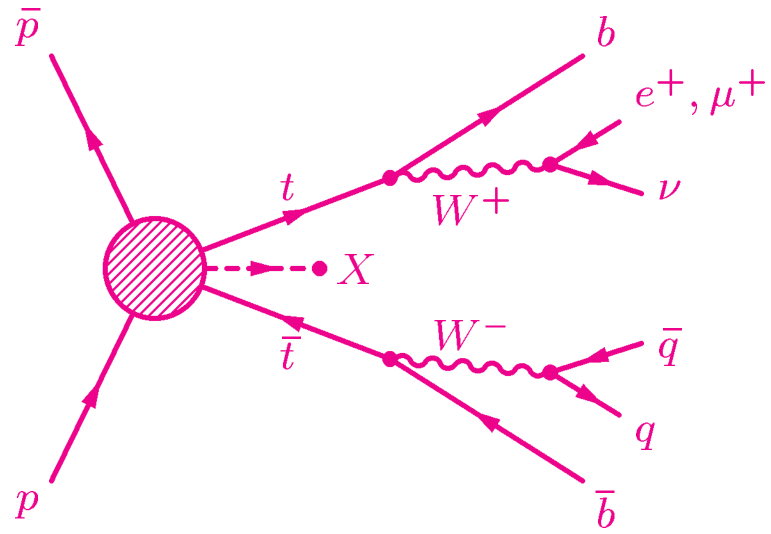
This distribution contains signal and background
From MC determine shape of X as a function of m_t
From MC & data determine shape of X for background



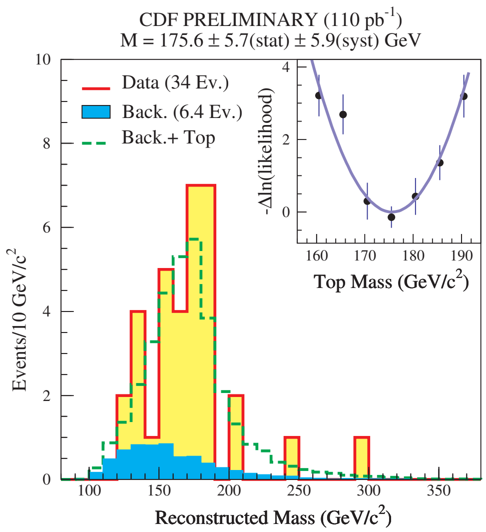
Do likelihood fit for m_t

Mass Measurements from ℓ + Jets Events

only 1 neutrino, so a constrained (2C) fit is possible



Simplest measurement is to select candidates and do likelihood fit to reconstructed mass distribution



requires tagged jet, 3 jets $E_T > 15$ GeV,
4th reconstructed jet, good fit

But one can do better!

Introduce New Event Selection (DØ)

- Want to distinguish top signal from background while avoiding any large correlations with top mass.

- Variables:

$$x_1 = \not{E}_T \qquad \text{(Missing } E_T\text{)}$$

$$x_2 = \mathcal{A} \qquad \text{(Aplanarity)}$$

$$x_3 = \frac{H_{T2} \equiv H_T - E_T^{\text{jet1}}}{|p_z(l)| + |p_z(\nu)| + \sum_j |p_z(j)|}$$

$$x_4 = \frac{\Delta R_{jj}^{\text{min}} E_T^{\text{min}}}{E_T^L}$$

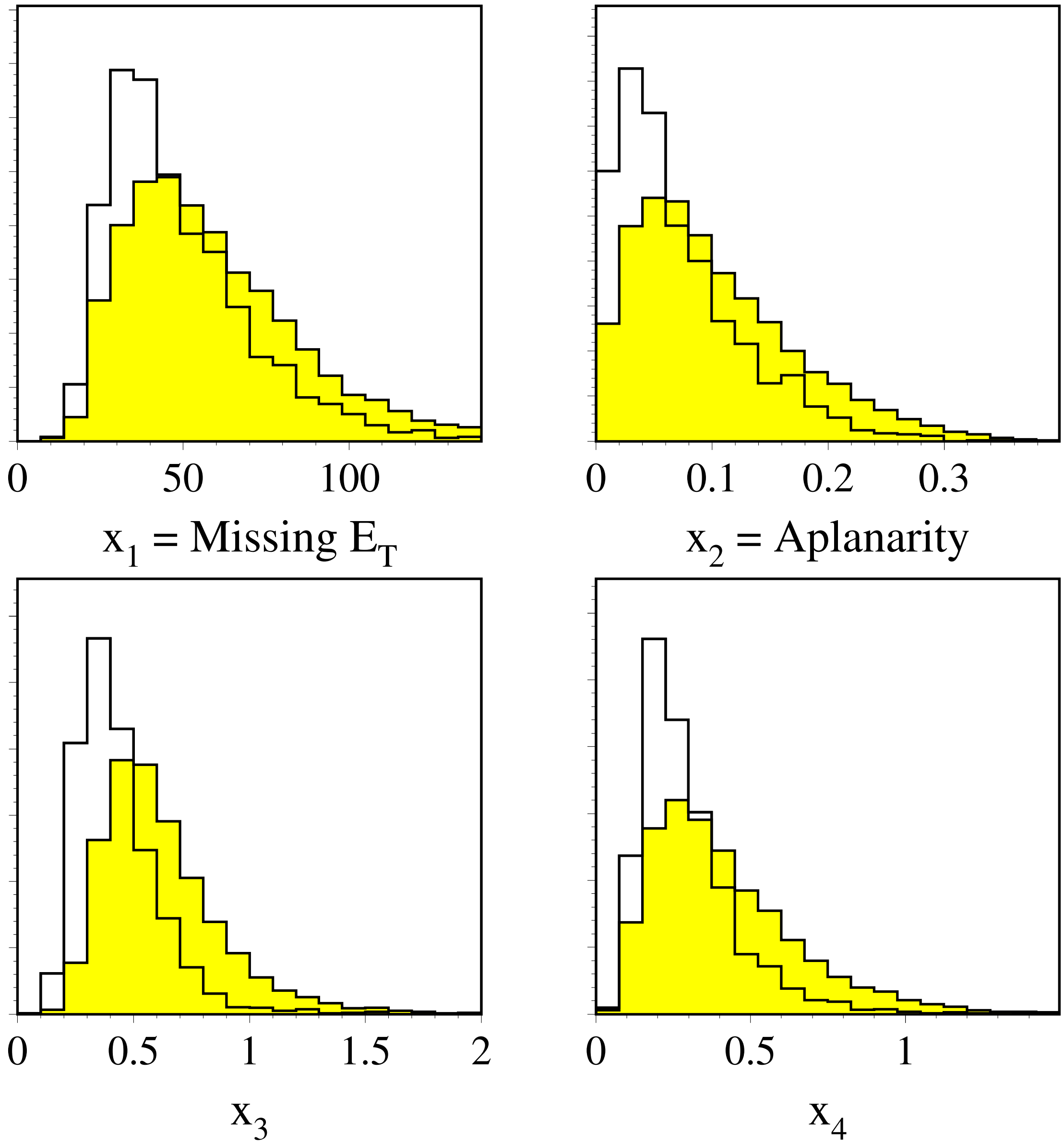
- x_3 measures the event centrality.

- x_4 measures the extent to which jets are clustered together.

- Combine these four variables into a multivariate discriminant $0 \leq \mathcal{D} \leq 1$

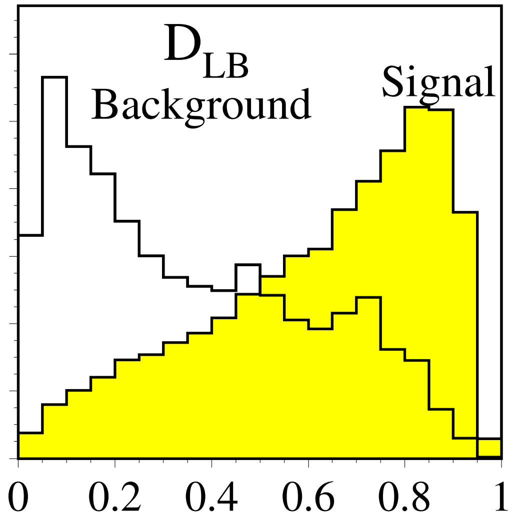
Discriminant Variables (DØ)

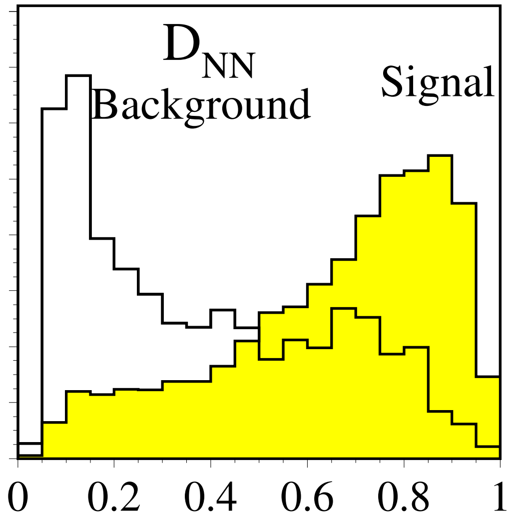
For Background and $m_t = 175\,\mathrm{GeV}/c^2$ Herwig top.



The Discriminants (DØ)

For Background and $m_t = 175\,\mathrm{GeV}/c^2$ Herwig top .





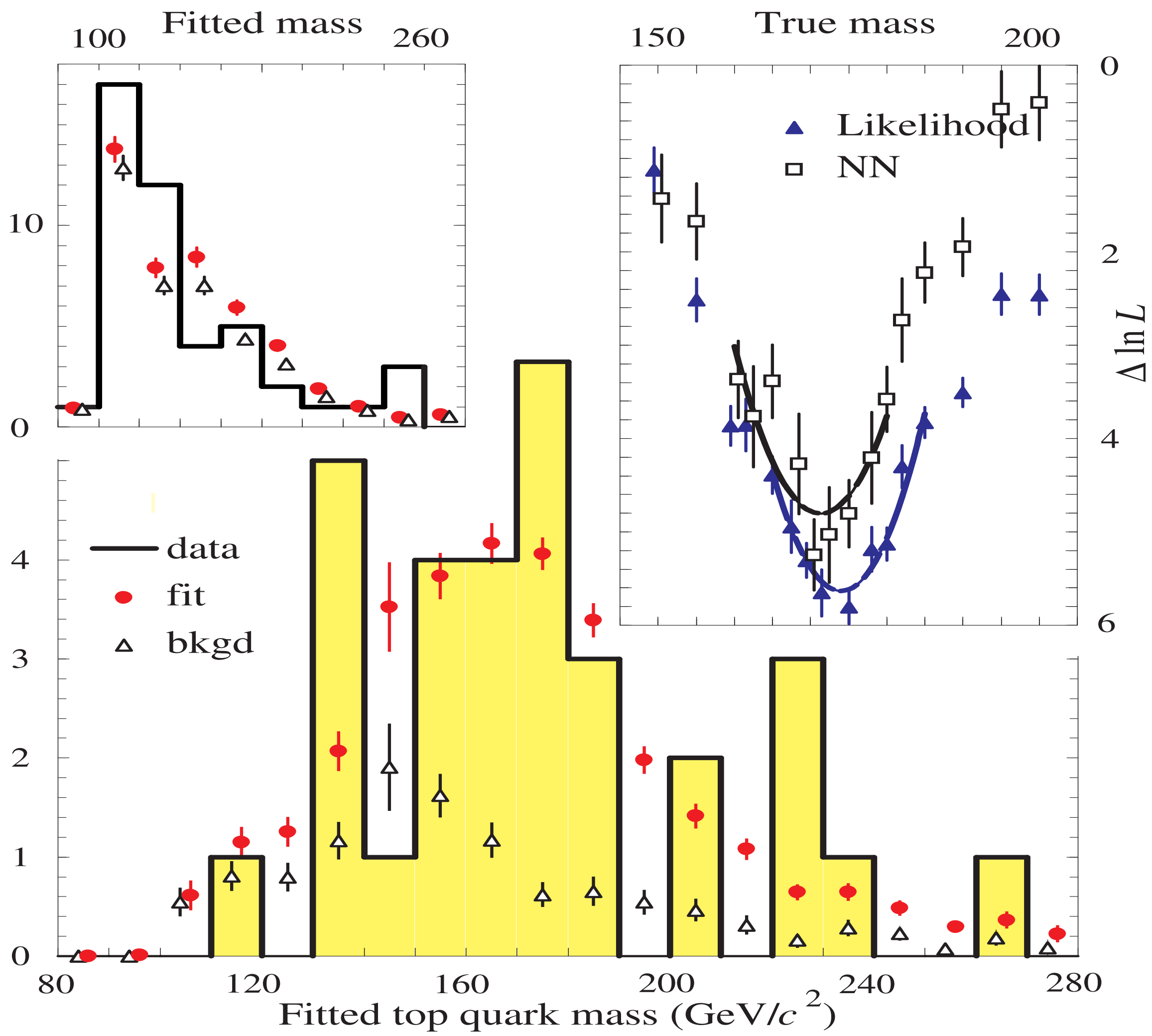
2D Likelihood fit

- Bin the data, signal, and background samples in (D,m_{fit}) plane

  D: Top probability m_{fit}: 80 - 280 GeV/c^2

- Fit signal + background models to the data

DØ Mass Measurement from ℓ+jets Events



	m_t	n_s	n_b
LB	174.0 ± 5.6 GeV/c^2	$23.8^{+8.3}_{-7.8}$	$53.2^{+10.7}_{-9.3}$
NN	171.3 ± 6.0 GeV/c^2	$28.8^{+8.4}_{-9.1}$	$48.2^{+11.4}_{-8.7}$

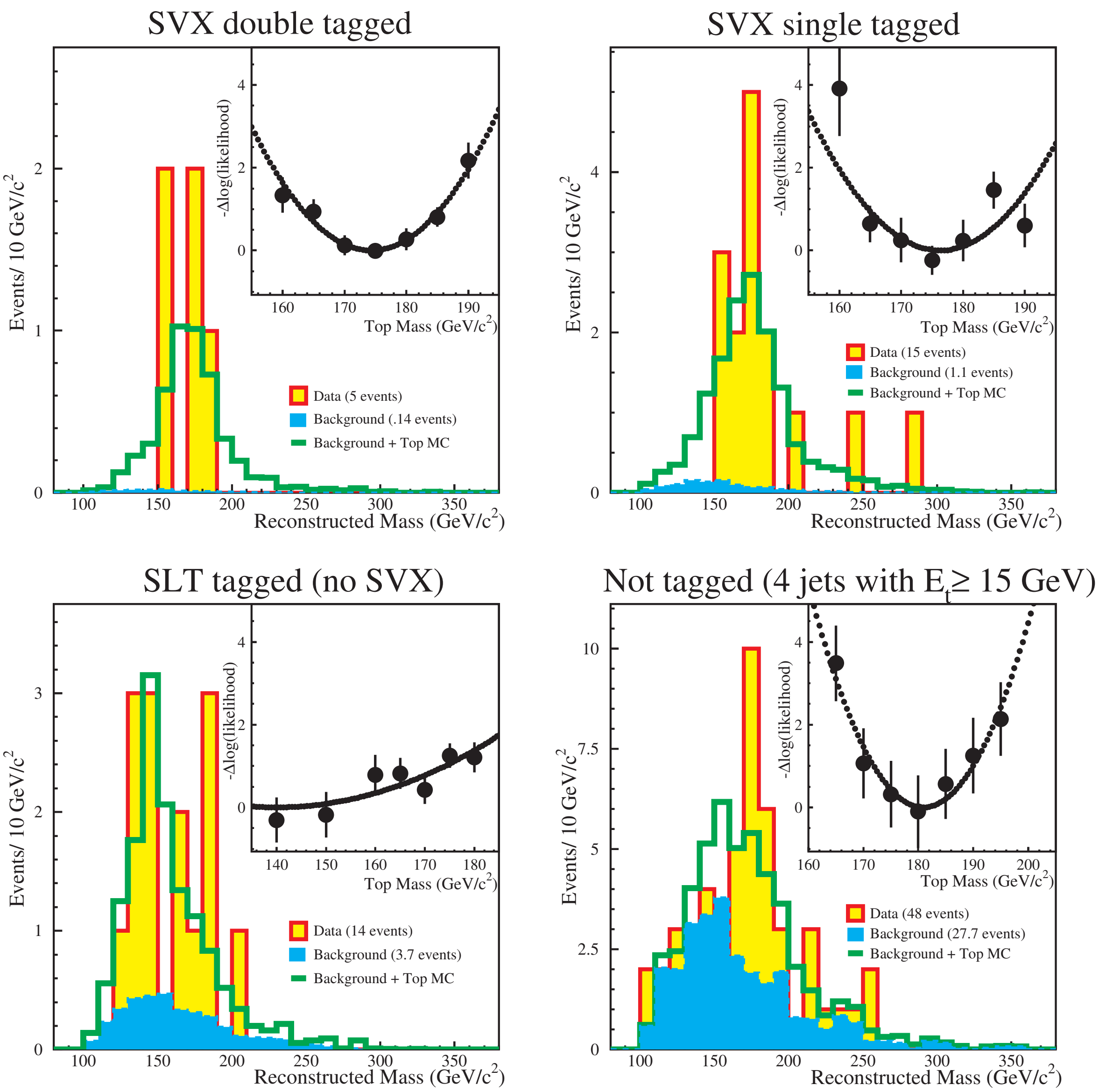
- Combined: $M_{\text{top}} = 173.3 \pm 5.6(\text{stat}) \pm 6.2(\text{sys})$ GeV/c^2. (88% correlation.)

CDF ℓ +jets Mass Measurement

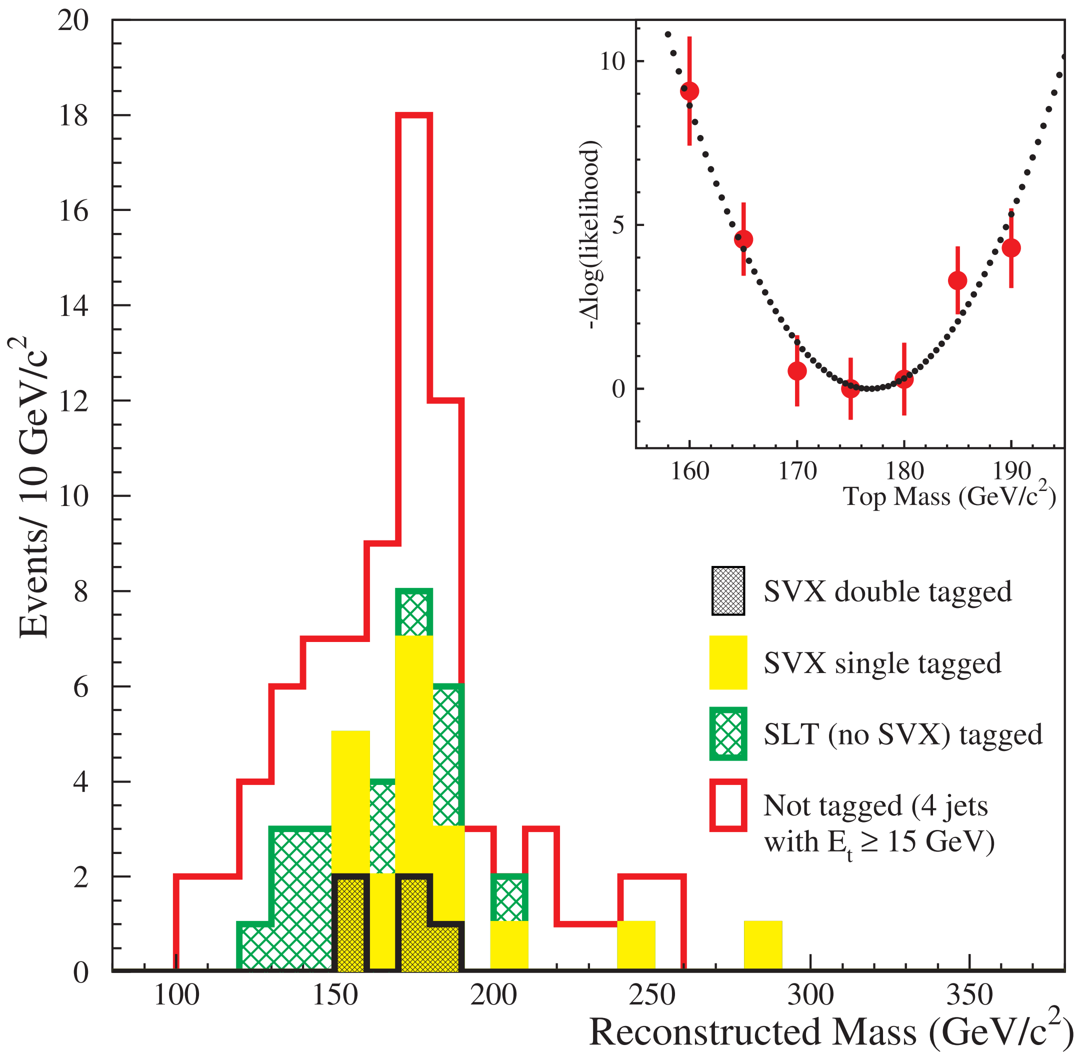
CDF divides candidates into 4 independent samples

Each sample is fit independently

Then the likelihood functions are multiplied together



CDF ℓ +jets Mass Measurement



$M_{\text{top}} = 176.8 \pm 4.4(\text{stat}) \pm 4.8(\text{sys})$ GeV/c^2

ℓ+jets Mass Result Systematic Uncertainties

DØ

Jet energy scale	4.0 GeV/c^2
Generator: Herwig/Isajet	3.3 GeV/c^2
Generator: Vecbos models	2.6 GeV/c^2
Multiple interactions	1.2 GeV/c^2
MC Statistics	0.8 GeV/c^2
LB/NN Difference	1.4 GeV/c^2
Likelihood fit	1.0 GeV/c^2
Total	6.2 GeV/c^2

CDF

Soft Gluon + Jet E_T Scale	3.6 GeV/c^2
Different MC Generators	1.4 GeV/c^2
Hard Gluon Effects	2.2 GeV/c^2
Fitting Methods	1.5 GeV/c^2
Tagging Bias	0.5 GeV/c^2
Background Spectrum	0.7 GeV/c^2
Monte Carlo Statistics	0.8 GeV/c^2
Total	4.8 GeV/c^2

Mass Measurement from Dilepton events

Motivation

There are three motivations, listed in order of current relevance:

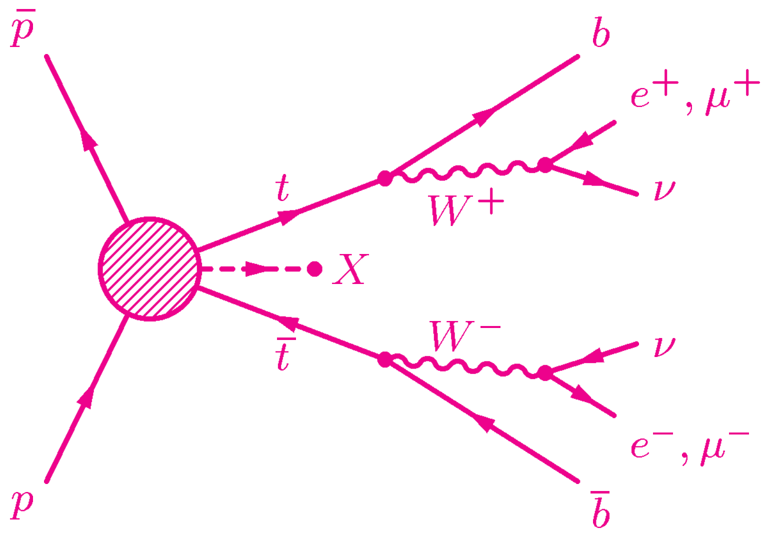
- Direct verification that the excess of dilepton events arises from the same source as the excess of lepton+jets events.
- Combining the dilepton result with that from the single lepton analysis, one is expected to reduce the uncertainty on m_t by $\sim 10\%$.
- The dilepton measurement might be expected to have smaller systematic uncertainties, and thus be the favored channel in future high-statistics measurements. Anything learned now can be applied then.

Mass Measurement from Dilepton events

Dilepton samples have very low backgrounds

Since the events have 2 leptonic W decays, there are 2 unmeasured neutrinos

A constrained fit is not possible



Two different strategies ...

Find kinematic variable with a strong mass dependence

> CDF uses 2 such variables: the jet energy spectrum and the invariant mass of the lepton-b pair

Calculate a weight as a function of m_t

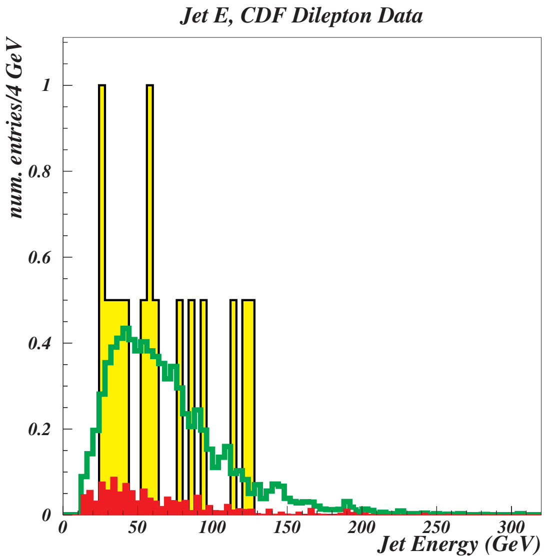
> DØ uses 2 methods to calculate relative probability as a function of assumed top mass

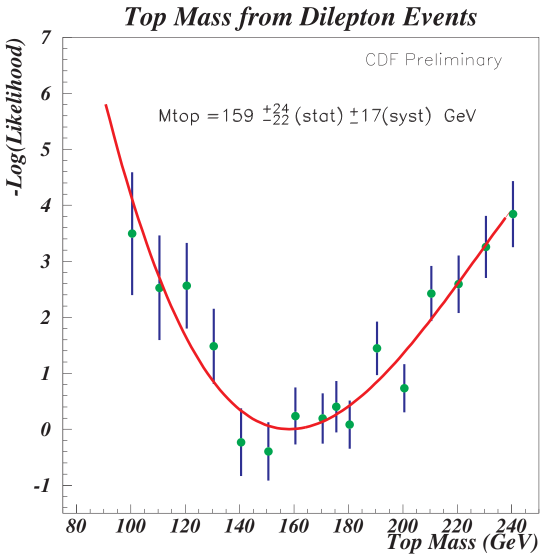
CDF Dilepton Mass Results

Jet Energy Distribution

compare the jet E with Monte Carlo templates

8 events, 2 entries/event, each entry has weight 0.5





$$M_{\text{top}} = 159^{+24}_{-22}(\text{stat}) \pm 17(\text{sys})\ \text{GeV}/c^2$$

Invariant mass of lepton-b pair

Use the approximate expression:

$$m_t^2 = m_W^2 + 2\frac{< m_{\ell b}^2 >}{1- < \cos(\theta_{\ell b}) >}$$

$< m_{\ell b}^2 >$ mean invariant mass of the lepton-b pair, measured

$< \cos(\theta_{\ell b}) >$ mean angle between lepton and b in the W rest system, from Monte Carlo

$$M_{\text{top}} = 159 \pm 21(\text{stat}) \pm 7(\text{sys})\ \text{GeV}/c^2$$

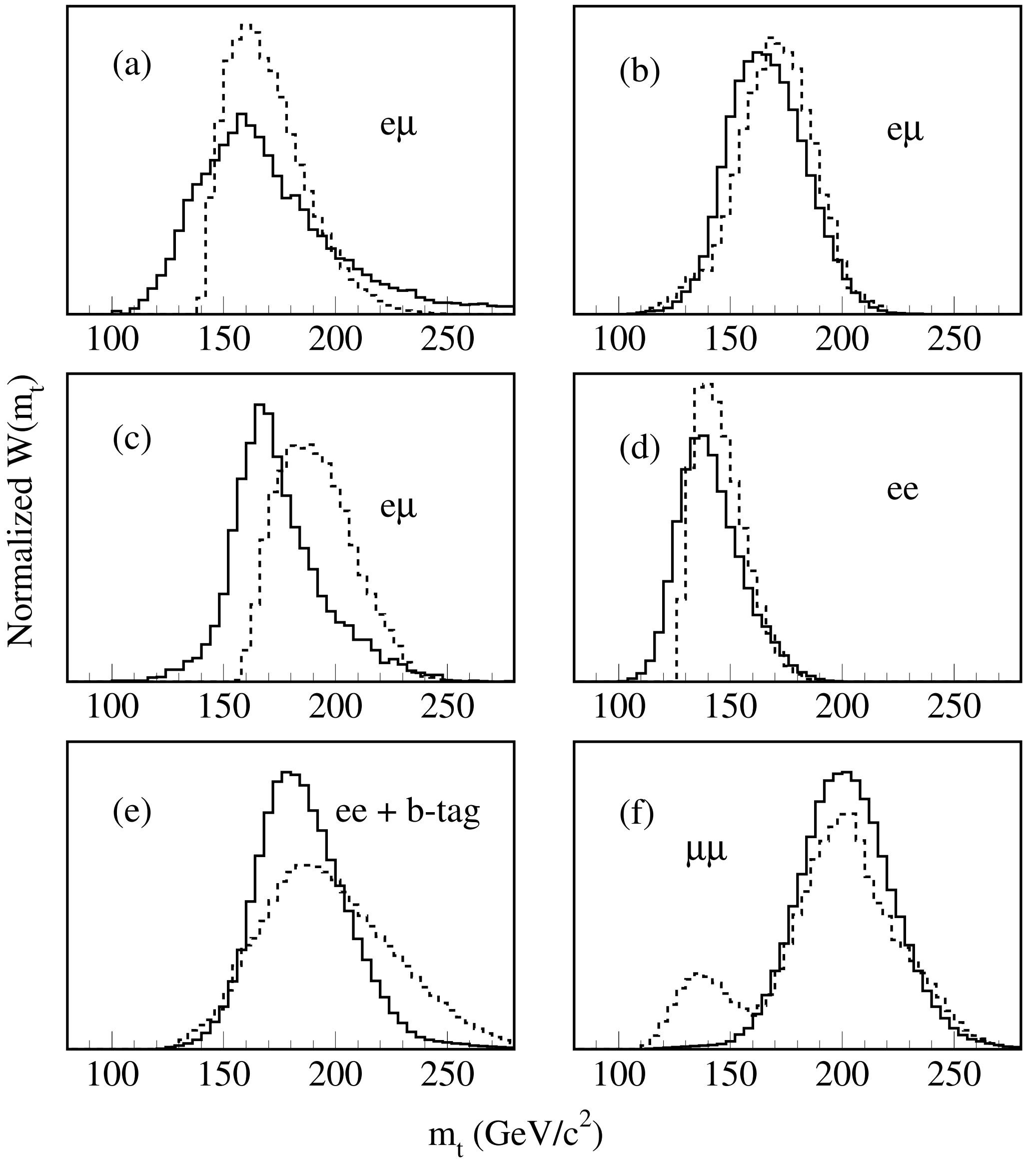
DØ dilepton mass analyses

Two methods for determining the relative probability of a solution

- Matrix Element Weighting (MWT)
  - Assume m_t
  - Event can then be solved
  - Assign a weight using the parton distribution functions and the lepton p_T's (an extension of ideas proposed by Kondo and Dalitz & Goldstein)
- Neutrino Weighting (νWT)
  - Assume m_t and rapidity for each neutrino
  - Event can then be solved without using the measured $\not{E}_T$
  - Assign a weight based on the agreement between the calculated neutrino p_T ($\vec{p_T}(\nu\nu)$) and the measured $\vec{\not{E}_T}$
- Points in common between the two methods
  - Smear the event many times to account for detector resolution and sum the resulting likelihoods
  - Sum over both possible pairings of b-jets with leptons

Dilepton Candidate Sample

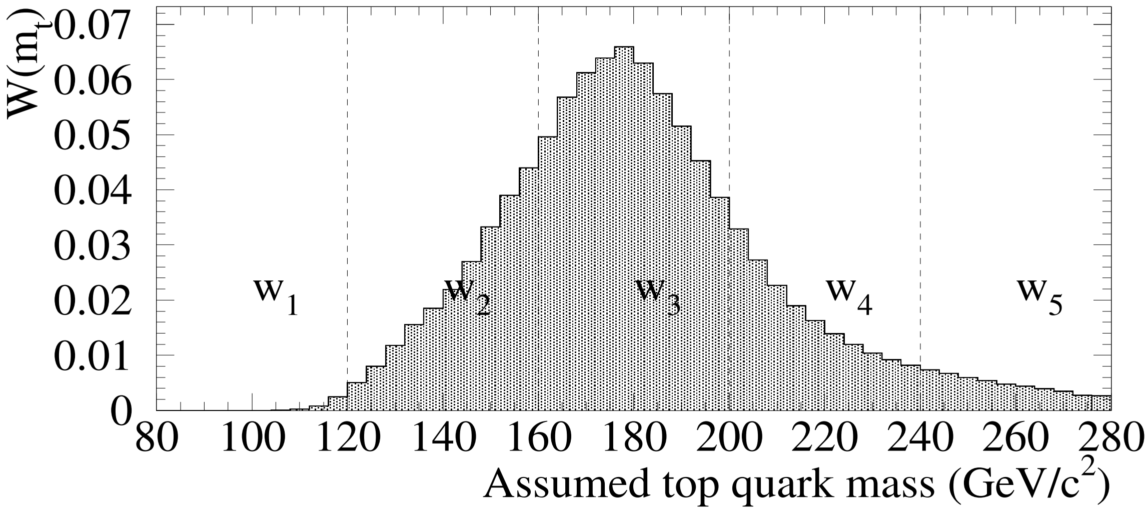
- Solid: νWT. Dashed: MWT.



Maximum Likelihood Fit

- Find the top quark mass most consistent with the entire data sample.

- Divide normalized $\mathcal{W}(m_t)$ into 5 bins.



- Describe events by 4 independent quantities (fraction/bin) $\mathbf{w} \equiv w_1 \ldots w_4$. Sum over all data.

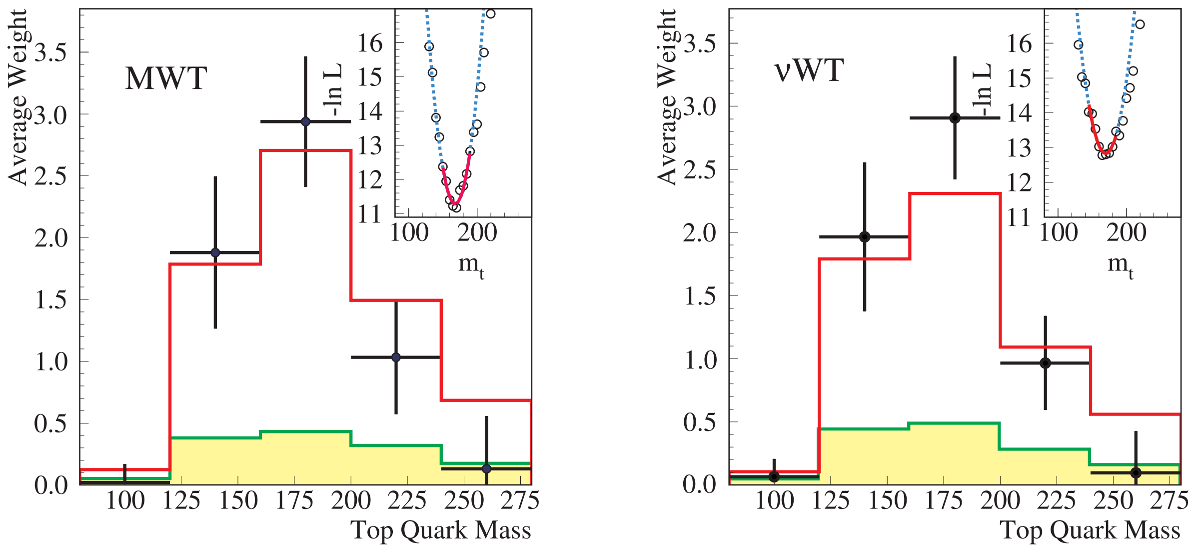
- Do a Maximum Likelihood fit for n_s, n_b using

$$L(m_t) = g(n_b)p(n_s + n_b)\frac{n_s f_s(\mathbf{w}|m_t) + n_b f_b(\mathbf{w})}{n_s + n_b}.$$

- Approximate f_s and f_b using MC.

- Plot $-\ln L$ versus m_t and fit a quadratic to the 9 points nearest the minimum.

Dilepton Results



- MWT: $m_t = 168.1 \pm 12.4(\text{stat.})$ GeV/c^2.
- νWT: $m_t = 169.9 \pm 14.8(\text{stat.})$ GeV/c^2.
- Systematic errors:

Jet Scale	2.5
Signal Generator	1.7
BG Shape	1.2
Mult. Int.	1.3
Likelihood fit	1.3
Total	3.7

- Combined:

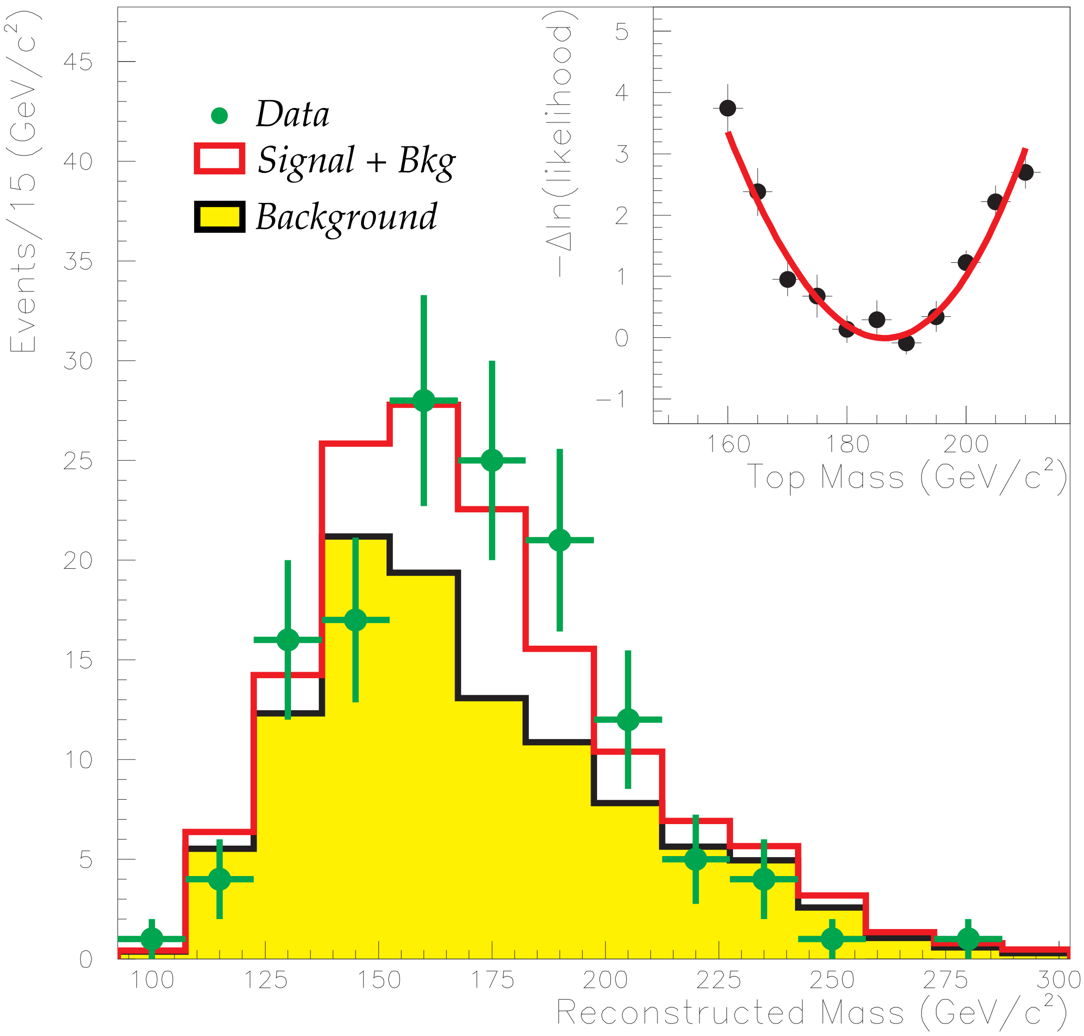
$$\boxed{m_t = 168.4 \pm 12.3(\text{stat.}) \pm 3.7(\text{syst.})\ \text{GeV}/c^2}$$

CDF alljets Mass Measurement

No neutrino, measure all particles in event

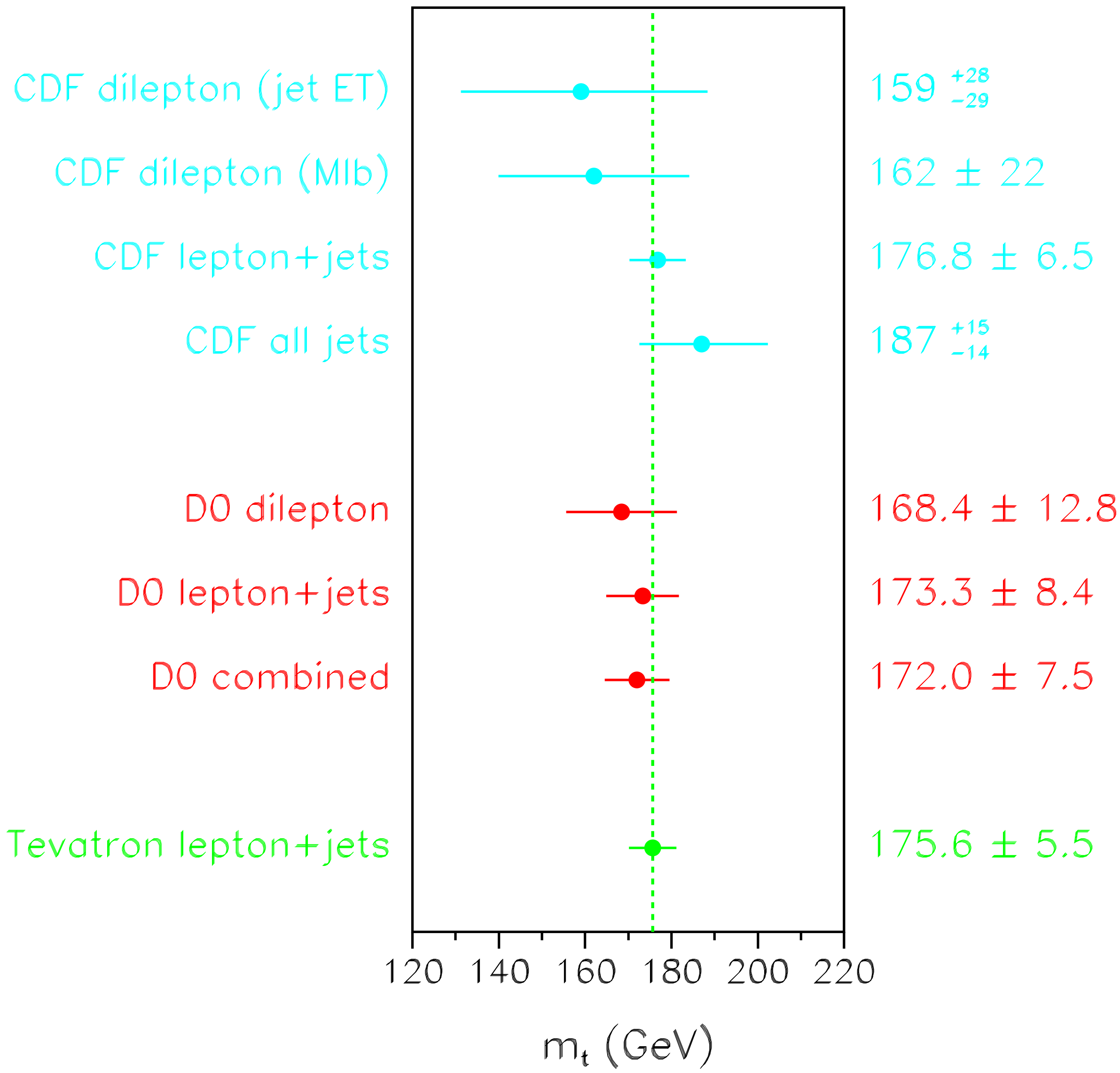
CDF selects vertex tagged candidates

3C fit

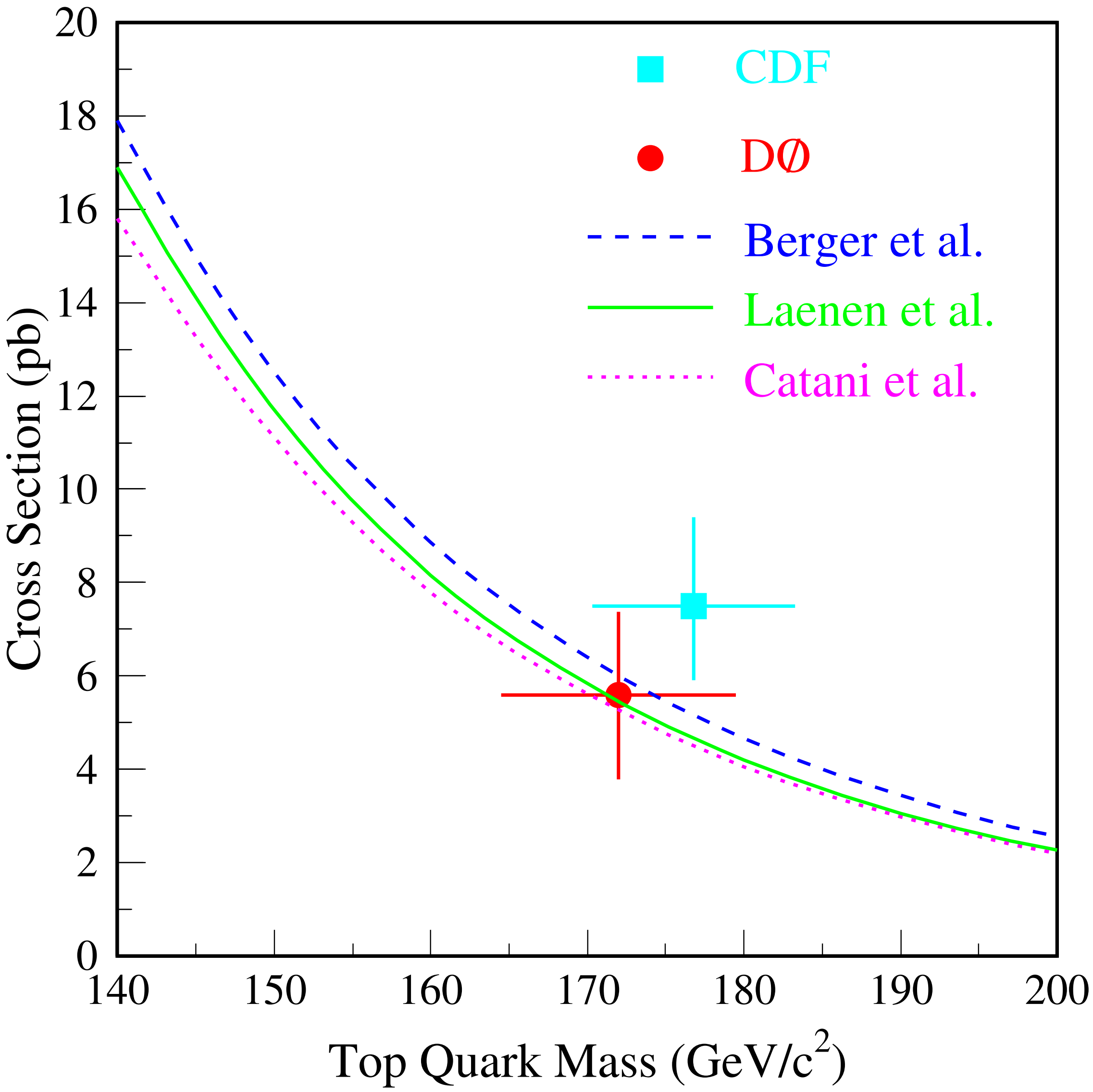


$M_{\text{top}} = 187 \pm 8(\text{stat})^{+13}_{-12}(\text{sys})\ \ \text{GeV}/c^2$

Summary of m_t measurements



$t\bar{t}$ cross section vs m_t



$\sigma_{t\bar{t}} = 7.5^{+1.9}_{-1.6}$ pb at $m_t = 175$ GeV$/c^2$ CDF

$\sigma_{t\bar{t}} = 5.6 \pm 1.8$ pb at $m_t = 172$ GeV$/c^2$ DØ

Kinematic properties of the $t\bar{t}$ system

Important probe of non-SM physics

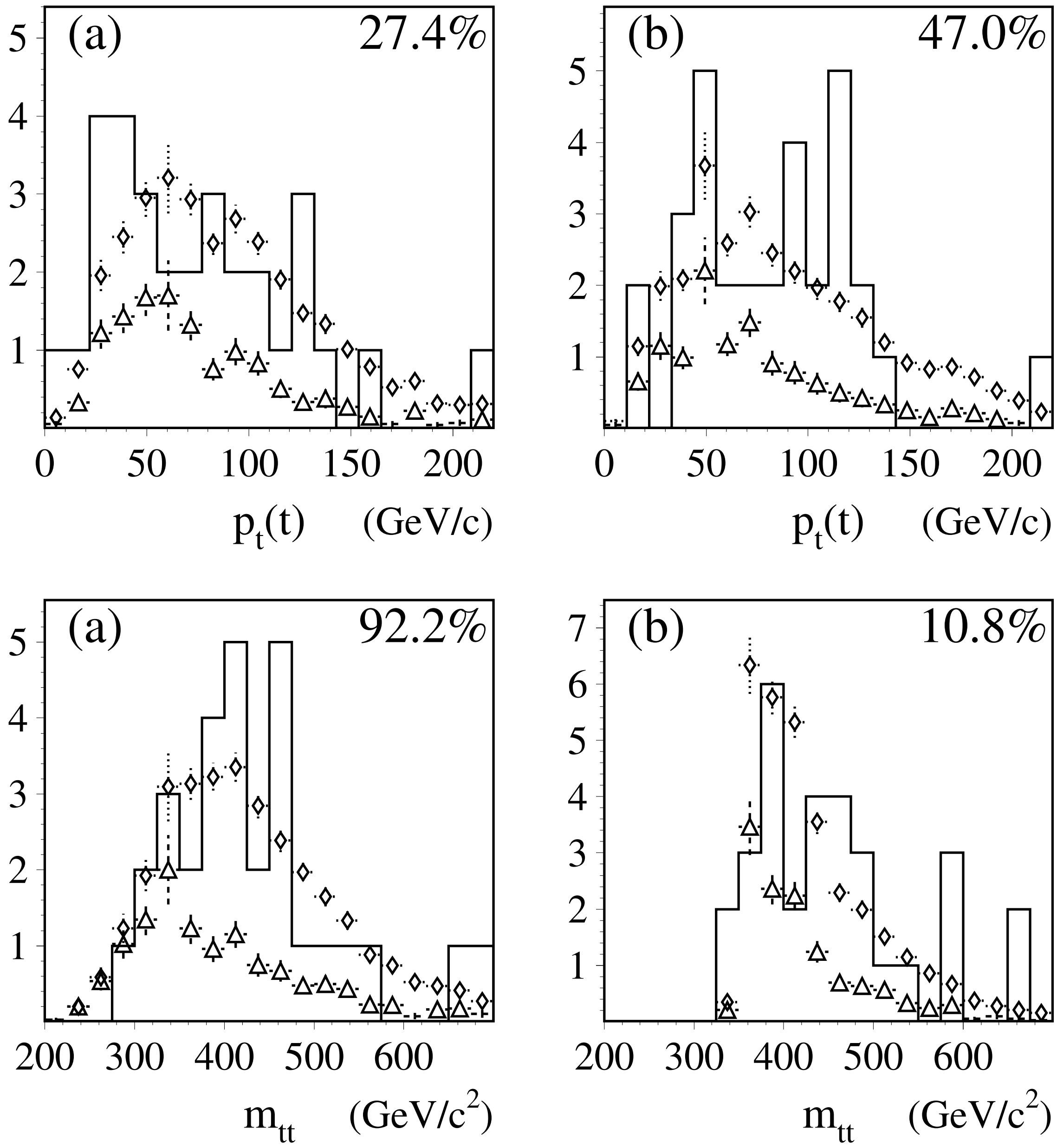
- Reconstruct $t\bar{t}$ system using the mass fitter

- Compare observed distributions of different kinematic properties of data with SM expectation for $t\bar{t}$ + background

- for example
  - Mass($t\bar{t}$)
  - $p_T(t\bar{t})$
  - $\Delta\phi(t\bar{t})$
  - $\Delta\eta(t\bar{t})$
  - $p_T(t)$ (leptonic and hadronic)

- Observed distributions biased by detector resolution, selection, fitting

$p_T(t)$ and $m_{t\bar{t}}$ (DØ)



2C fit

3C fit

$m_t = 173.3$ GeV/c^2

Other CDF top quark results

- Upper limit on top decaying to charged Higgs

  $m_{H^\pm} > 147$ GeV/c^2 ($\sigma_{t\bar{t}} = 5.0pb, \tan\beta = \infty$)
  $m_{H^\pm} > 158$ GeV/c^2 ($\sigma_{t\bar{t}} = 7.5pb, \tan\beta = \infty$)
  submitted to PRL, Fermilab-Pub-97/058-E

- Upper limit on the FCNC decays of the top quark

  BR($t \to q\gamma$) $< 2.9\%$ at 95% CL

  BR($t \to qZ$) $< 44\%$ at 95% CL

- Measurement of
  $R_b = \Gamma(t \to Wb)/\Gamma(t \to Wq) = |V_{tb}^{\mathrm{3gen}}|^2$

$$R_b = 1.23^{+0.37}_{-0.31}$$

Future top physics at the Tevatron

- Tevatron run 2 begins late 1999
- Expect 2 fb^{-1} per experiment (20 times current data of 100 pb^{-1}).
- $\sqrt{s} = 2.0$ TeV (35% increase in $t\bar{t}$ cross section relative to current $\sqrt{s} = 1.8$ TeV).
- Expect top event yield about 30 times current sample:

	Events per Experiment	S/B
Dilepton	200	5/1
ℓ+3jets+b-tag	1400	3/1
ℓ+4jets+2b-tags	600	12/1
Single Top	180	1/2

Conclusions

Both Tevatron experiments have measured the $t\bar{t}$ production cross section:

$\sigma_{t\bar{t}} = 7.5^{+1.9}_{-1.6}$ pb at $m_t = 175$ GeV/c^2 CDF

$\sigma_{t\bar{t}} = 5.6 \pm 1.8$ pb at $m_t = 172$ GeV/c^2 DØ

Both Tevatron experiments have measured the top quark mass:

$m_t = 176.8 \pm 6.5$ GeV/c^2 CDF

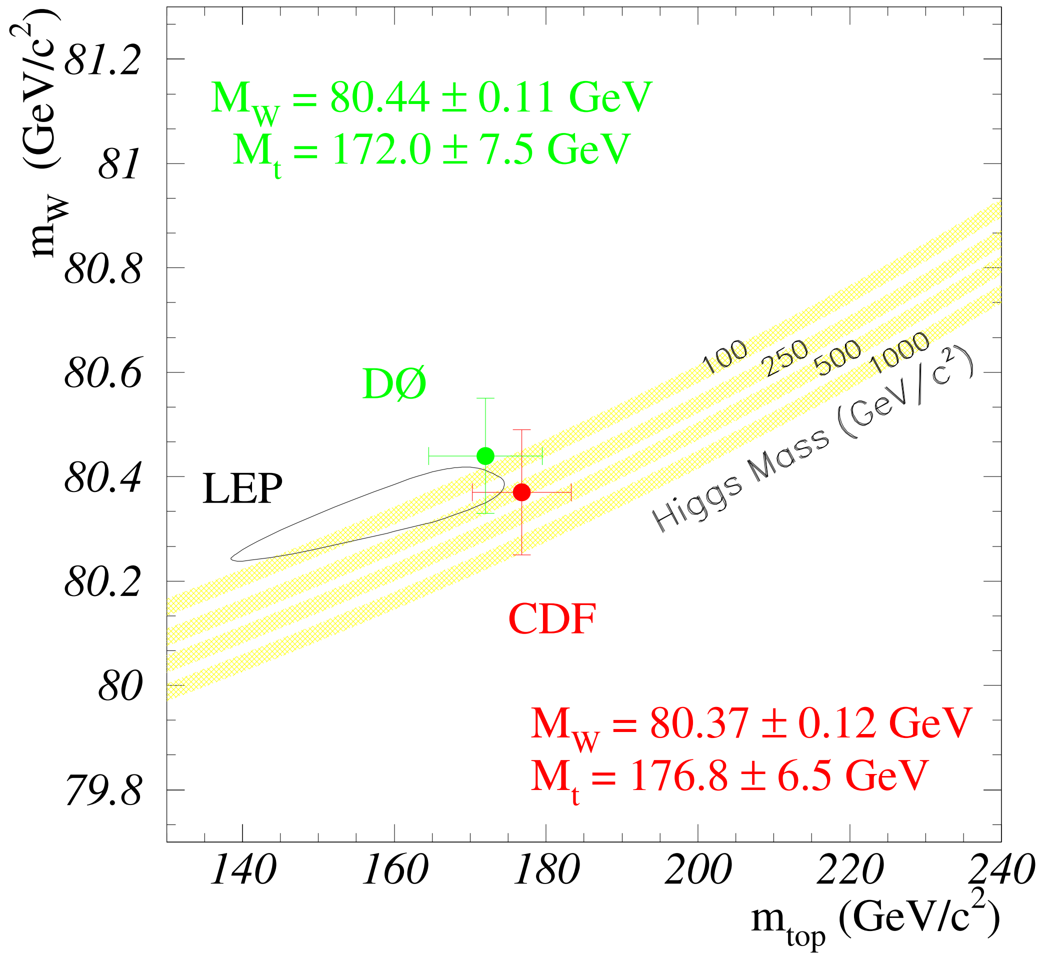
$m_t = 172.0 \pm 7.5$ GeV/c^2 DØ

$m_t = 175.6 \pm 5.5$ GeV/c^2 Tevatron

Both experiments are actively exploring other areas of the top sector, looking for deviations which might point to new physics

Expect 30 times current top quark event samples in run 2 (begins lates 1999)

M_W versus m_t



M_W = 80.44 ± 0.11 GeV
M_t = 172.0 ± 7.5 GeV
DØ
LEP
CDF
M_W = 80.37 ± 0.12 GeV
M_t = 176.8 ± 6.5 GeV
100
250
500
1000
Higgs Mass (GeV/c²)
m_W (GeV/c²)
81.2
81
80.8
80.6
80.4
80.2
80
79.8
140
160
180
200
220
240
m_top (GeV/c²)