Review of Top Physics at Hadron Colliders

- Top at the Tevatron
  - Cross Section
  - Mass
- The Future
  - Tevatron
  - LHC

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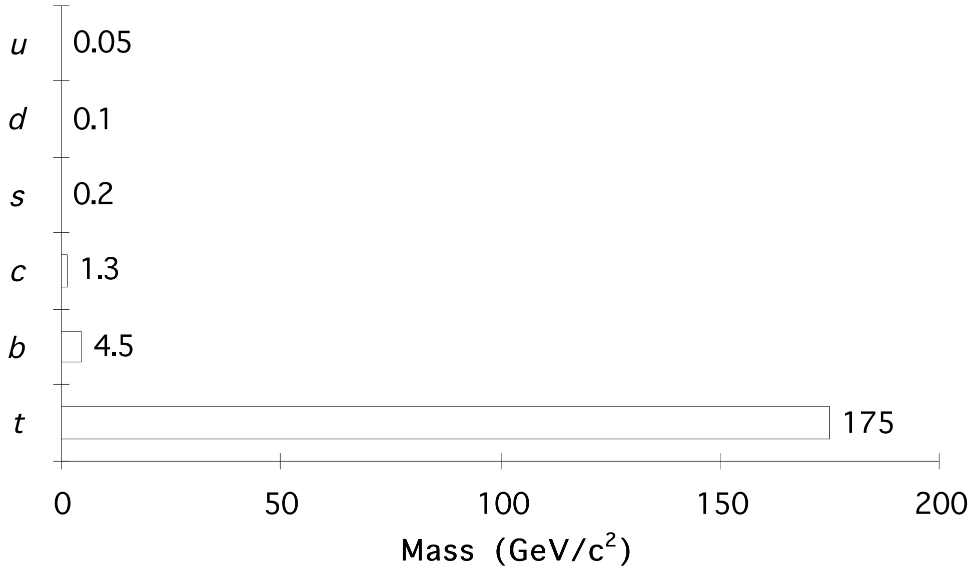
Particle Physics

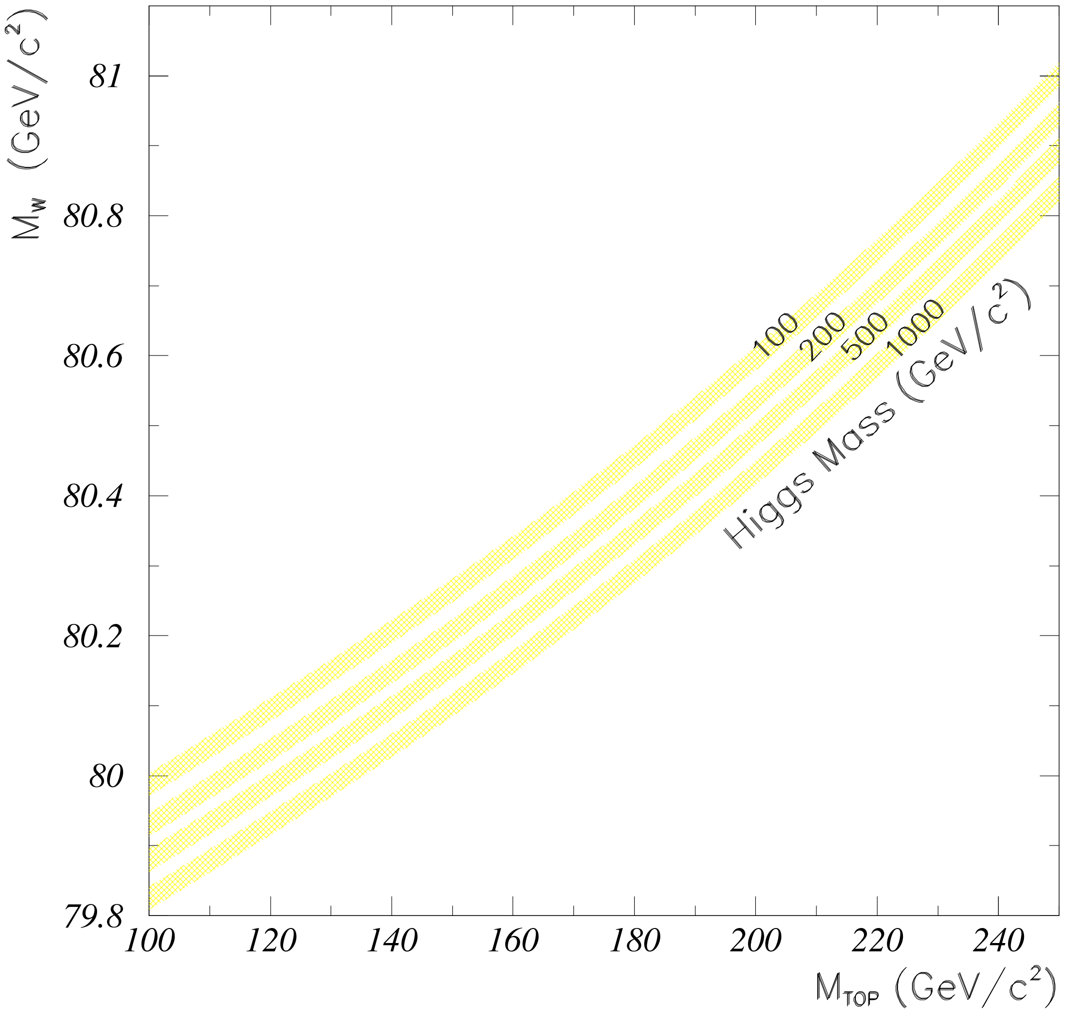
Introduction

- The top quark is young
  - Discovery: February 1995
- A good place to look for physics beyond the standard model
  - → Measurements of standard model parameters(M_{Top}).
  - → Direct searches for new objects and new phenomena.



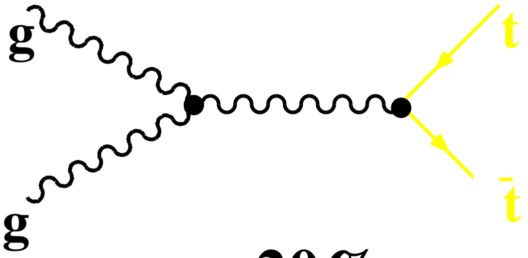
Introduction

- **And, of course, the Higgs hunt!**

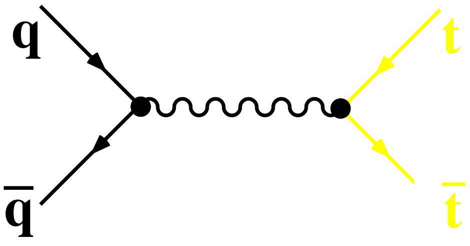


Top Production

- Most top quarks are pair produced:



20%



80%

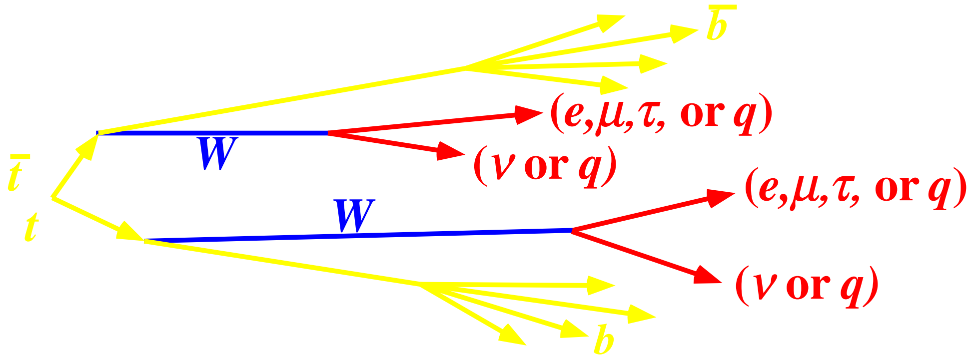
- Production is small:
  - $\int \mathcal{L} dt > 100\ \mathbf{pb}^{-1}$.
  - $> 5 \times 10^{12}\ \bar{p}p$ collisions
  - Only about 500 $\bar{t}t$ pairs produced!

$$\frac{\sigma_{\bar{t}t}}{\sigma_W} \sim 10^{-3}$$

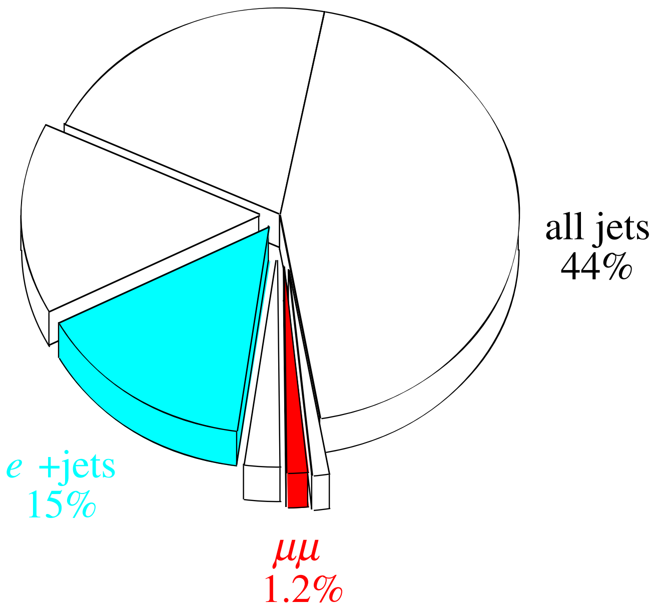
$$\frac{\sigma_{\bar{t}t}}{\sigma_{\text{inelastic}}} \sim 10^{-9}$$

Top Decay

- Standard Model Top decays almost 100% $t \to Wb$.
- Classify channels by W decay modes.
  - $W \to \ell\nu_\ell$
  - $W \to \bar{q}q$



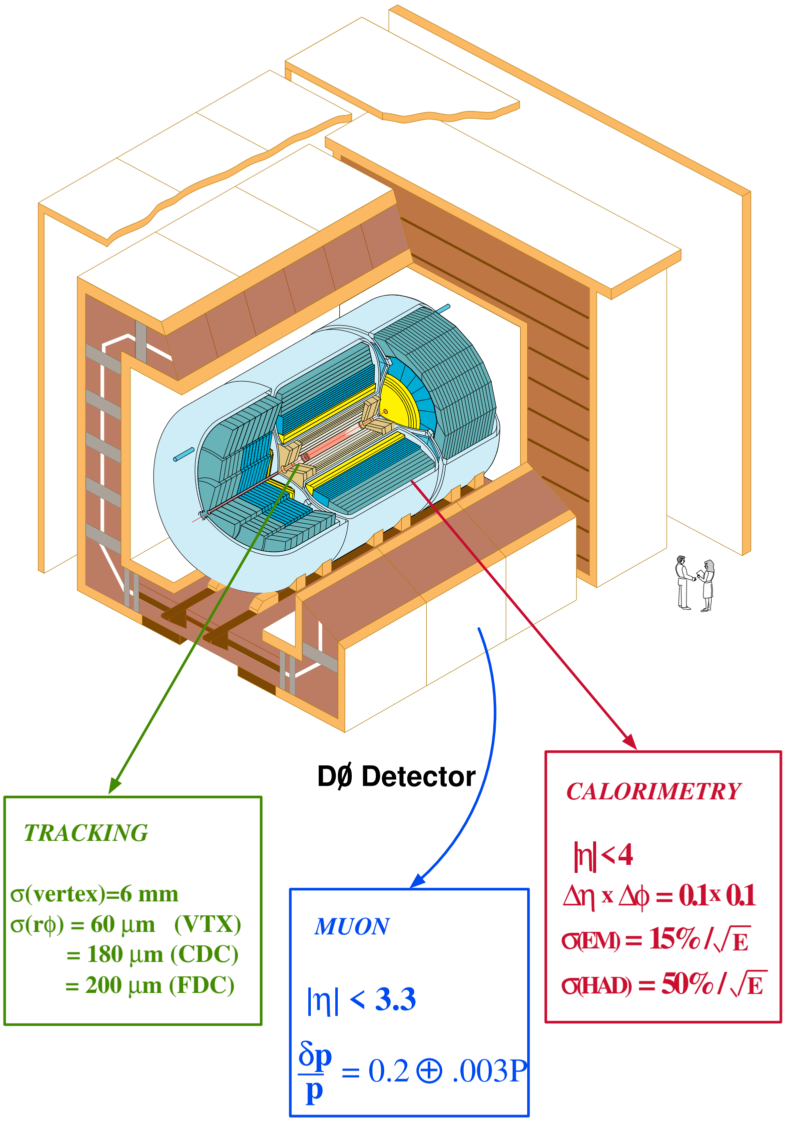
Top Decay Channels Used



- $\sigma_{\bar{t}t}$ is calculated in $\mu\mu$, ee, $e\mu$, e+jets, and μ+jets.
- A $\sigma_{\bar{t}t}$ is also found in the all jets channel.
- e+jets and μ+jets are used to find M_{Top}.
- M_{Top} is also determined in the All jets and dilepton channels.
- Both experiments are starting to look at the τ+X channels

The Detectors

- The detectors are very similar.
- DØ has complete calorimeter coverage
- CDF has a Silicon Vertex Detector



DØ Detector

TRACKING

$\sigma(\text{vertex}) = 6$ mm
$\sigma(r\phi) = 60\ \mu$m (VTX)
$= 180\ \mu$m (CDC)
$= 200\ \mu$m (FDC)

MUON

$|\eta| < 3.3$

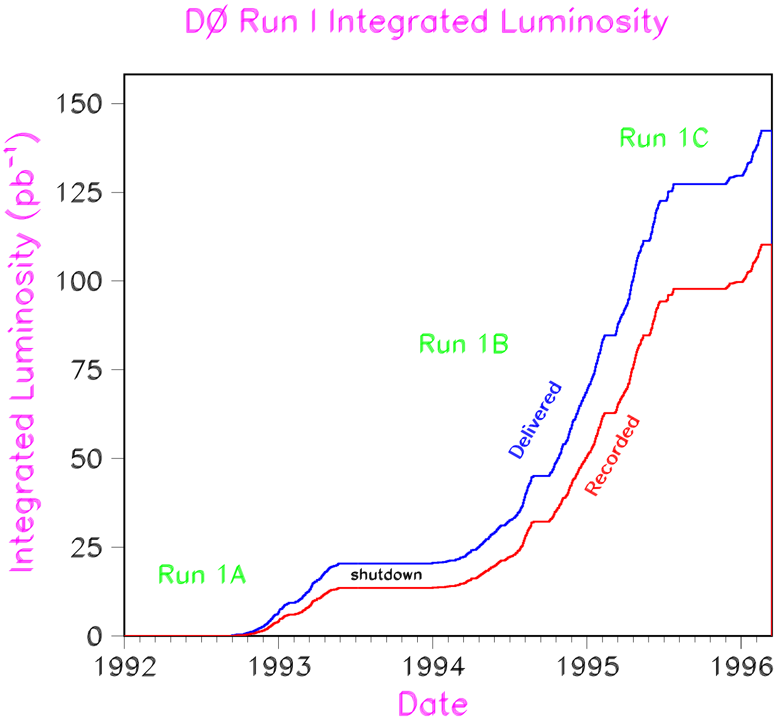
$$\frac{\delta p}{p} = 0.2 \oplus .003P$$

CALORIMETRY

$|\eta| < 4$
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
$\sigma(EM) = 15\% / \sqrt{E}$
$\sigma(HAD) = 50\% / \sqrt{E}$

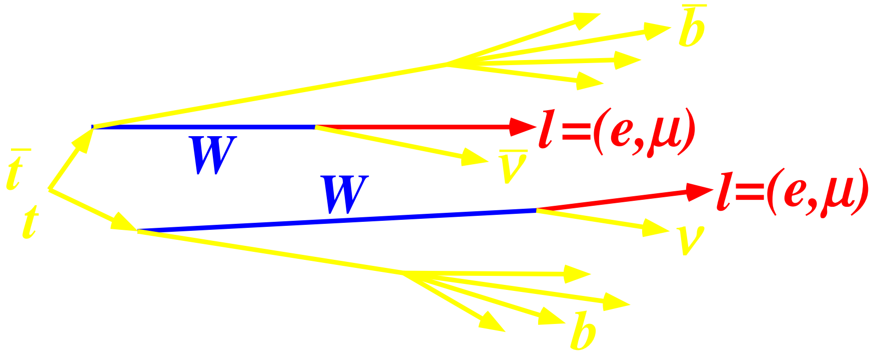
Looking For The Top Quark

The Data Set:



- **Dilepton:**
  - **(ee, $e\mu$, and $\mu\mu$) (CDF & DØ)**
  - **τ channels, others (DØ)**
  - **τe, $\tau\mu$ (CDF)**
- **Lepton + Jets (e and μ) (CDF & DØ)**
- **All Jets (CDF & DØ)**

Dilepton Channel



Signature of the Dilepton Decay:

- **Two isolated, high p_T leptons (e or μ).**
- **Large $\not{E}_{\mathrm{T}}$**
- 2 or more jets

Features:

- Signal rate is small, but
- Physics backgrounds are small too.
- More difficult for mass fitting (two neutrinos)

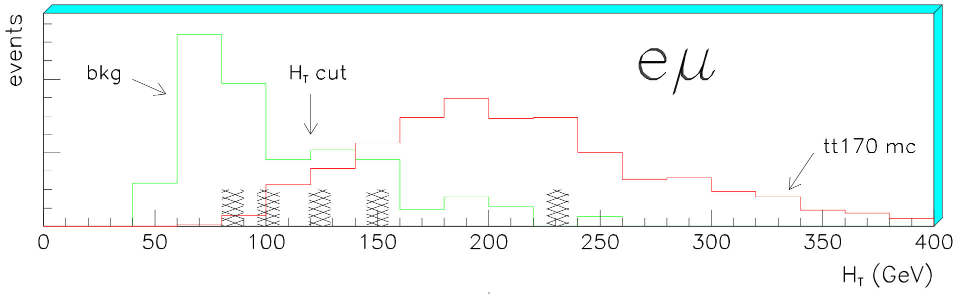
Dilepton Backgrounds

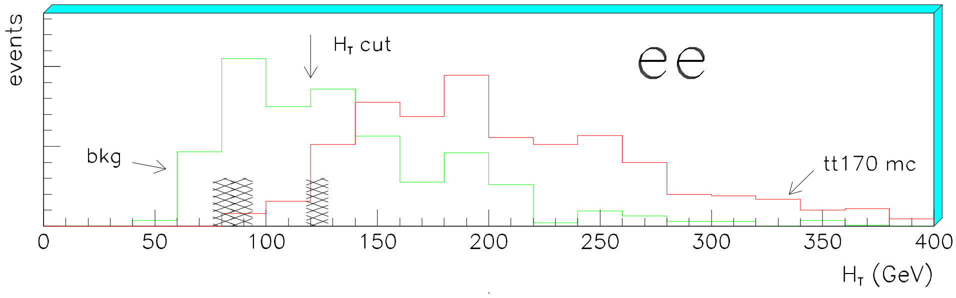
- Physics Backgrounds
  - Same signature as top
  - Such as $WW \rightarrow e\mu$X
  - Use Monte Carlo to estimate.
- Fake Backgrounds
  - Jet faking a lepton
  - Large $\not\!\!E_{\mathrm{T}}$ (fluctuations and resolution)
  - Cosmics
- At DØ, H_T is a powerful cut.

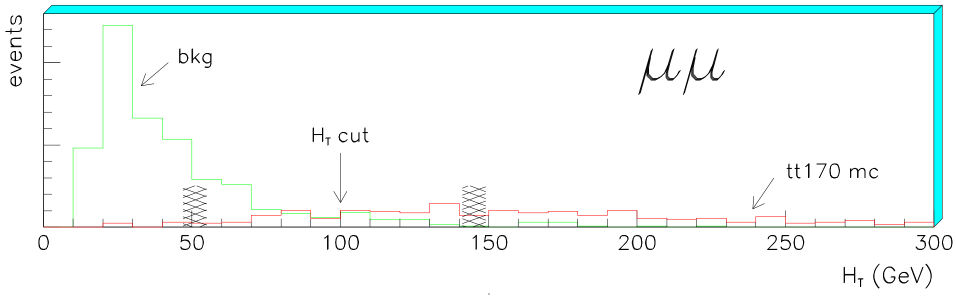
$$H_T = \sum p_T^{\ell} + \sum E_T^{\mathrm{jets}}$$

H_T in the Dilepton Channels (DØ)

- **All cuts applied except H_T**
- **Background**
- **Monte Carlo $\bar{t}t$ (170 GeV/c^2)**







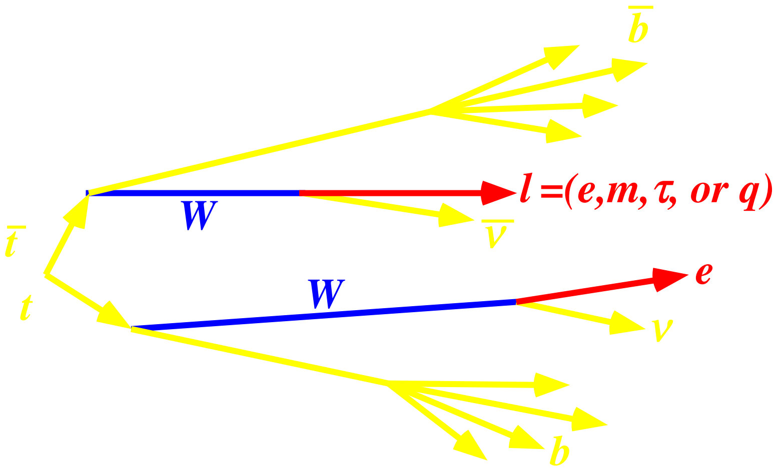
Typical Selection Cuts

Dilepton Event Summary

	DØ	CDF
$e\mu$	**3**	**7**
Background	**0.4 ± 0.1**	**0.76 ± 0.21**
Expected	**1.7 ± 0.3**	**2.4 ± 0.2**
ee **or** $\mu\mu$	**2**	**2**
Background	**1.2 ± 0.4**	**1.23 ± 0.36**
Expected	**1.4 ± 0.1**	**1.6 ± 0.2**
Expected evaluated at	M_{Top}= **170 GeV/c^2**	M_{Top}= **175 GeV/c^2**

- **Cross section for Dilepton Channels in a minute.**
- **Expected is the Laenen *et al* calculation.**

DØ $e\nu$ Channel



- Extend search into τ channels and
- Small part of charged lepton phase space

Signature:

- Single high p_T lepton
- Large $\not\!\!E_{\rm T}$
- Two or more high-p_T jets

Features:

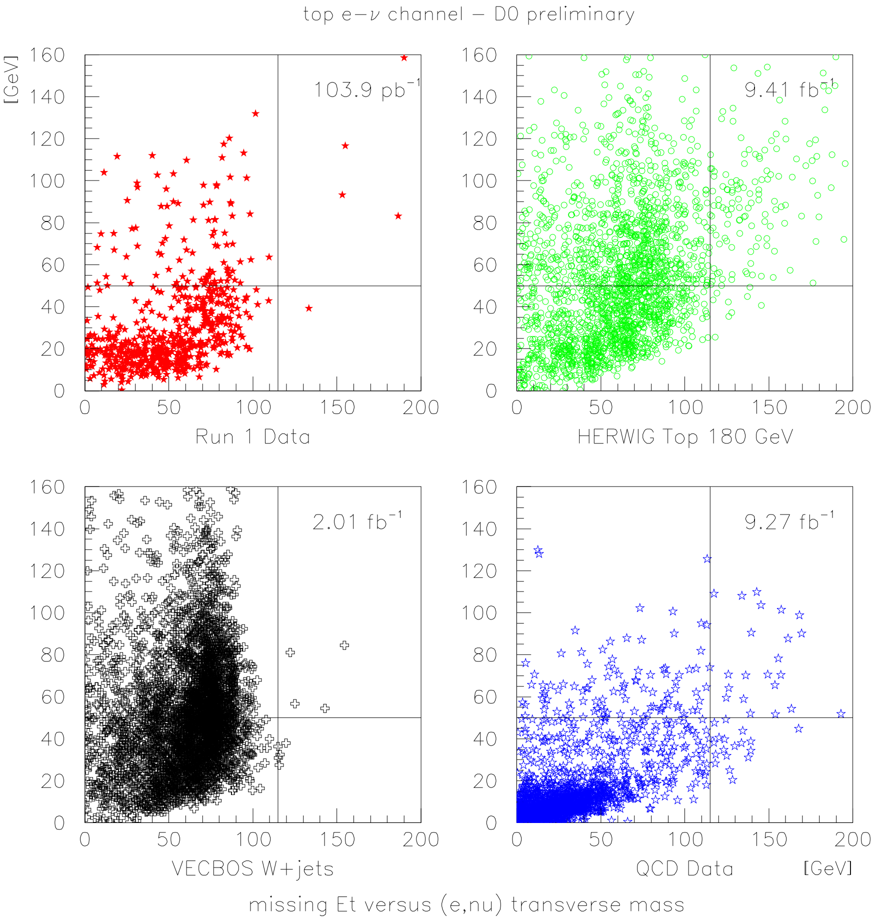
- Restricted section of charged dilepton channels
- Orthogonal to other channels by construction.

Largest Backgrounds:

- W+jets production
- Multi-jet events

$e\nu$ M_T Cut

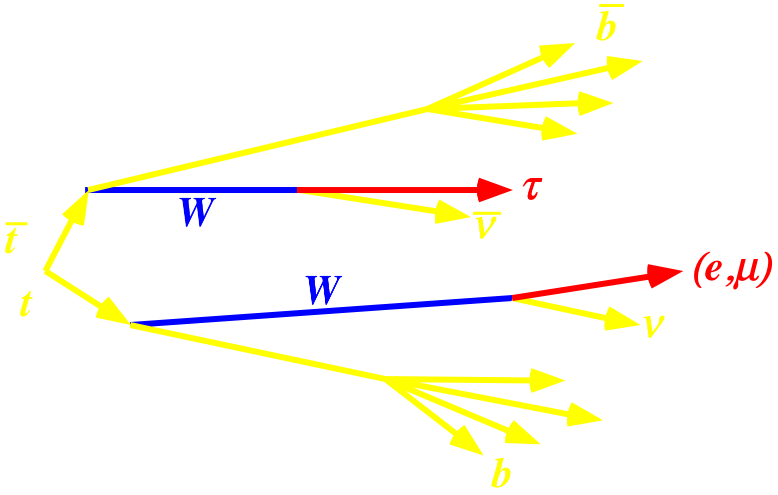
- M_T $(e,\not\!\!E_T)$ ***vs*** $\not\!\!E_T$
- **Explicitly reject events from other dilepton channels**



missing Et versus (e,nu) transverse mass

Selection Cuts

CDF τ Dilepton Analysis



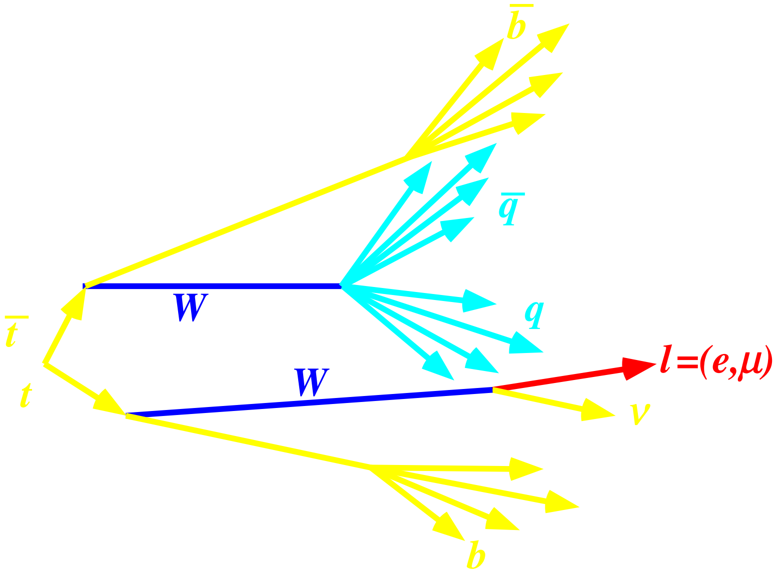
- Similar to DØ $e\nu$ analysis
- Have specific τ id requirement.
    - 1 or 3 prong τ decays

Summary:

	DØ*	CDF
Observed	2	4
Background	1.4 ± 0.5	1.96 ± 0.35
Expected	1.4 ± 0.1	0.7 ± 0.1
Expected evaluated at	M_{Top}= 170 GeV/c^2	M_{Top}= 175 GeV/c^2

* Only 88 pb^{-1} in this analysis

Lepton + Jets



Signature:

- **One high-p_T lepton (e or μ)**
- **Large $\not{E}_{\mathrm{T}}$**
- **4 or more jets, two from b decay.**

Largest Backgrounds:

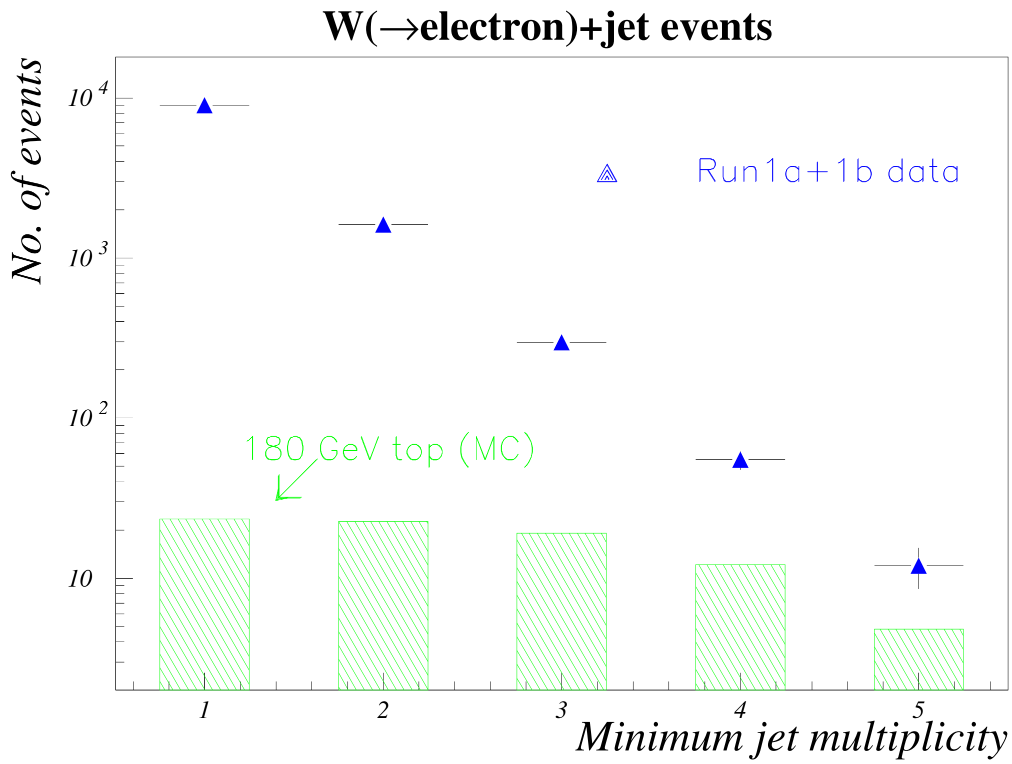
- W **jet production**
- **QCD production (fake leptons)**

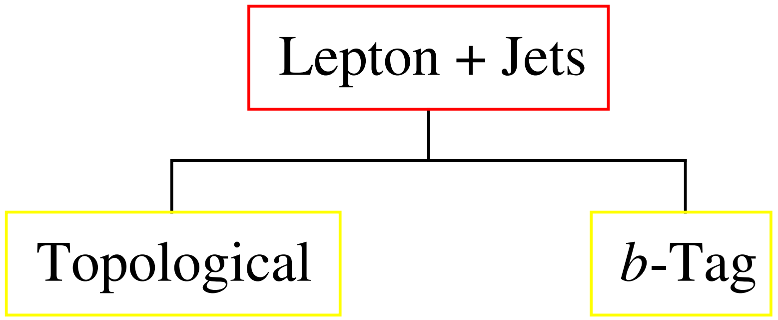
Further Requirements

Features:

- Backgrounds must be further suppressed with
  - Topological/kinematic restrictions:
    - Aplanarity
    - $H_T = \sum E_T^{\text{jets}}$
  - b-jet tagging
    - Low energy leptons from the semileptonic b decay
    - Displaced vertex b tag (CDF)
- Good top mass determination.

Lepton + Jets

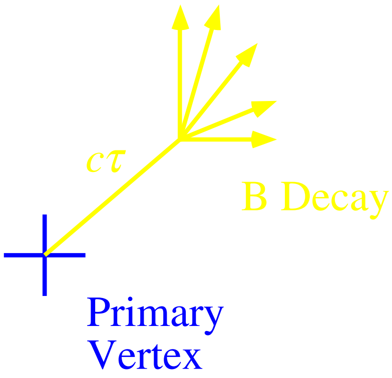


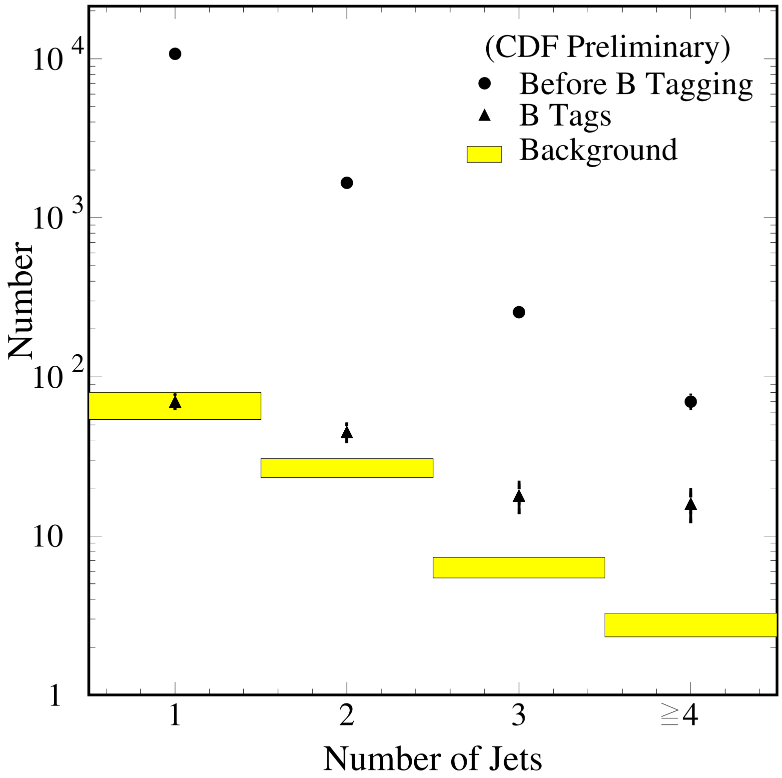

Lepton + Jets

Topological

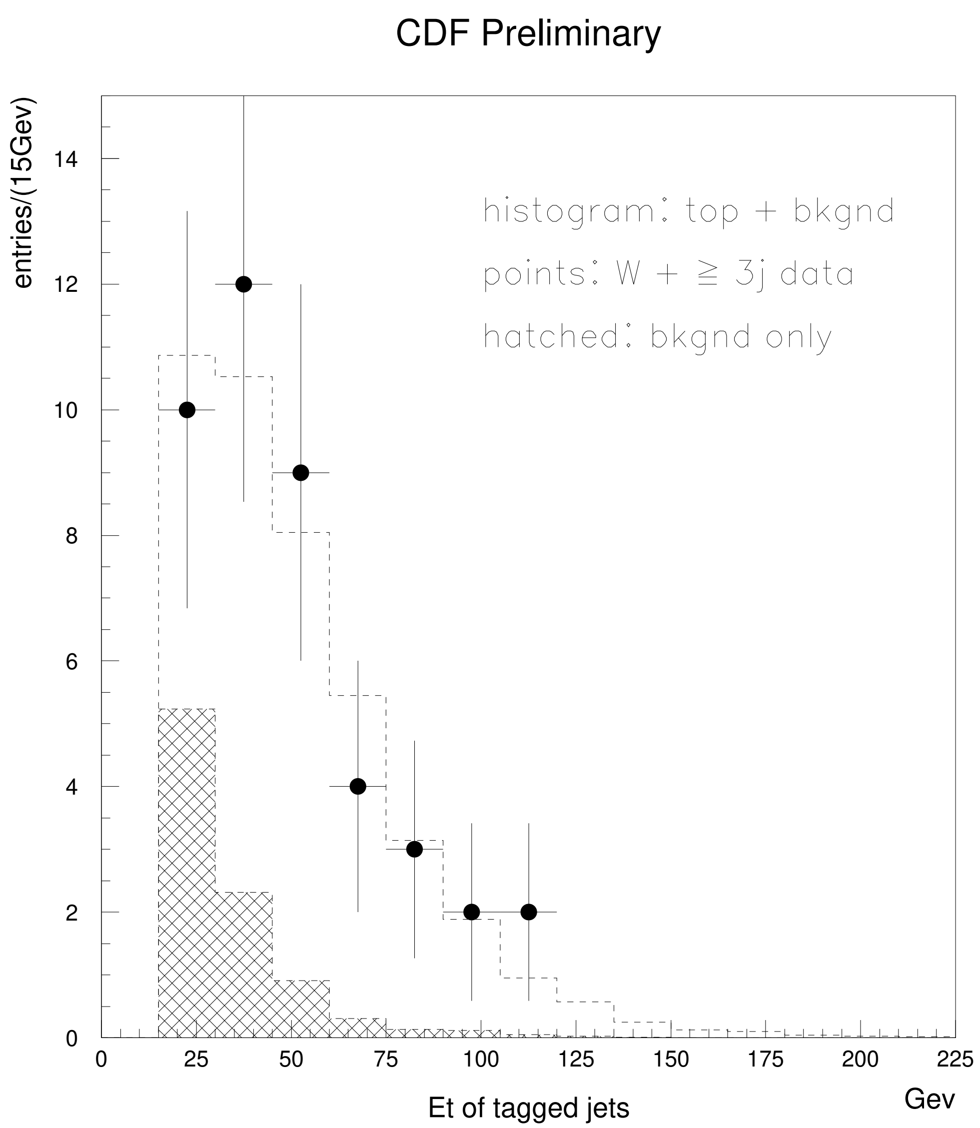
b-Tag

b-Tagging

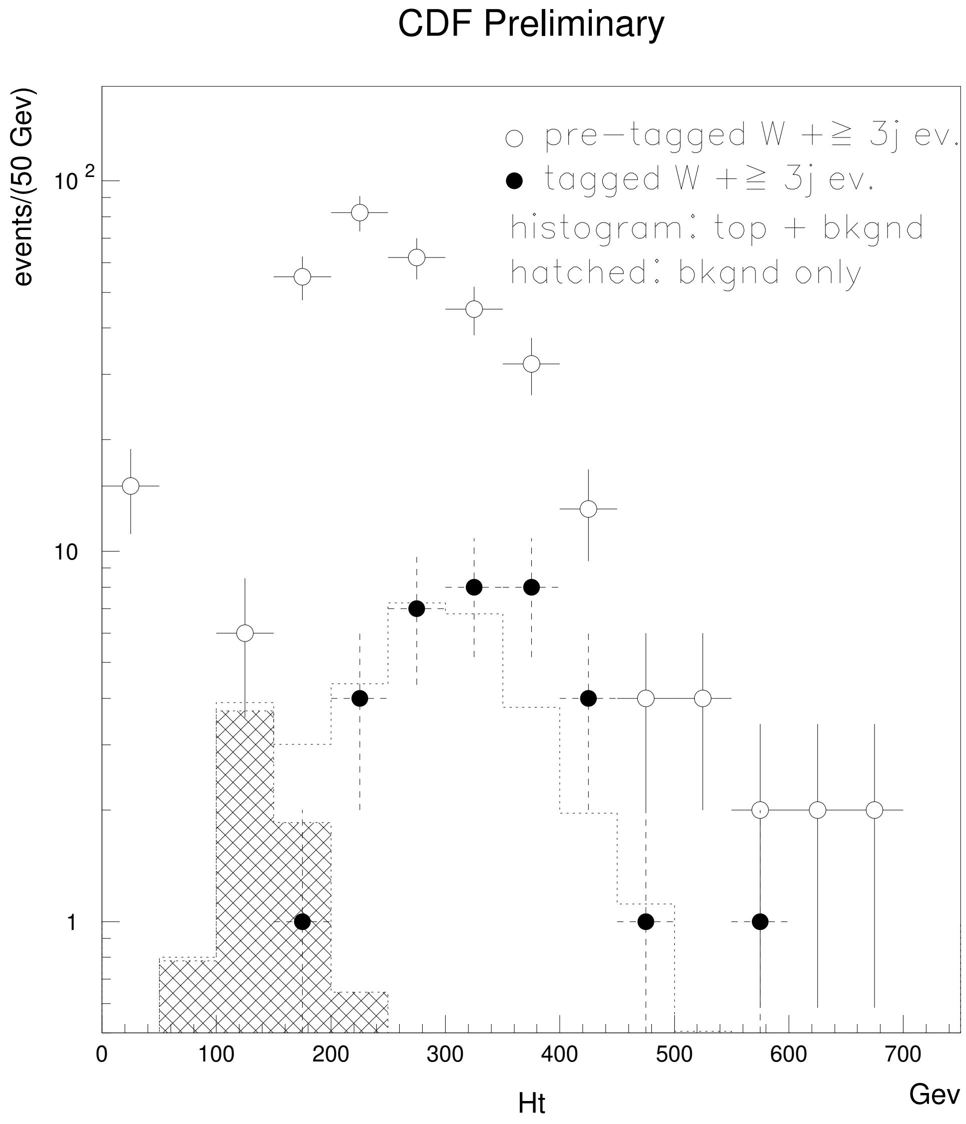

cτ
B Decay
Primary
Vertex


(CDF Preliminary)
● Before B Tagging
▲ B Tags
Background
Number
1
10
10 2
10 3
10 4
1
2
3
≥4
Number of Jets

SVX E_T


CDF Preliminary
entries/(15Gev)
histogram: top + bkgnd
points: W + ≧ 3j data
hatched: bkgnd only
0
2
4
6
8
10
12
14
0
25
50
75
100
125
150
175
200
225
Et of tagged jets
Gev

$\mathbf{SVX}\ H_T$



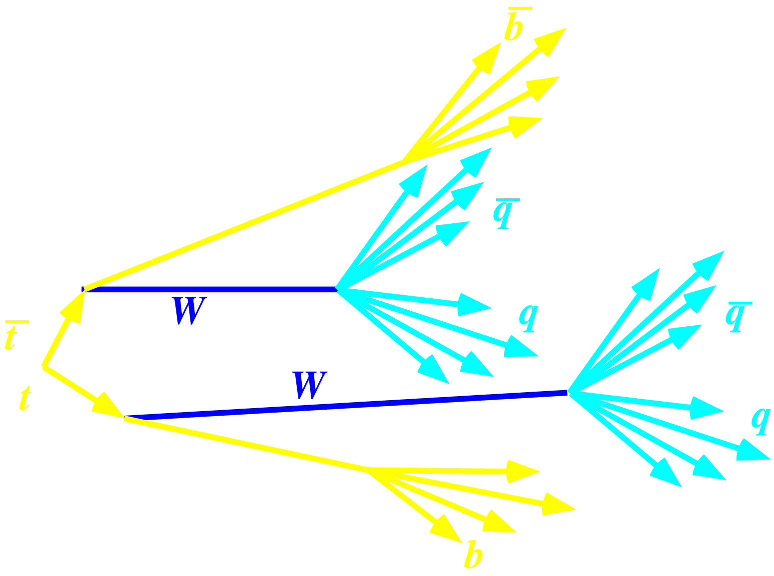
Lepton + Jets Summary

Sample	DØ	CDF
Topological		
Observed	21	22*
Background	9.2 ± 2.4	7.2 ± 2.1
Expected	12.9 ± 2.1	-
Lepton tag		
Observed	11	40
Background	2.5 ± 0.4	24.3 ± 3.5
Expected Yield	5.2 ± 1.0	9.6 ± 1.7
Displaced Vertex		
Observed		34
Background		8.0 ± 1.4
Expected		19.8 ± 4.0
Expected Evaluated at	M_{Top}= 170 GeV/c^2	M_{Top}= 175 GeV/c^2

* Only 67 pb^{-1} in the CDF event shape analysis

CDF's channels are not mutually exclusive

All Jets Channel



Signature:

- at least 6 jets, 2 from b quarks

Largest Backgrounds:

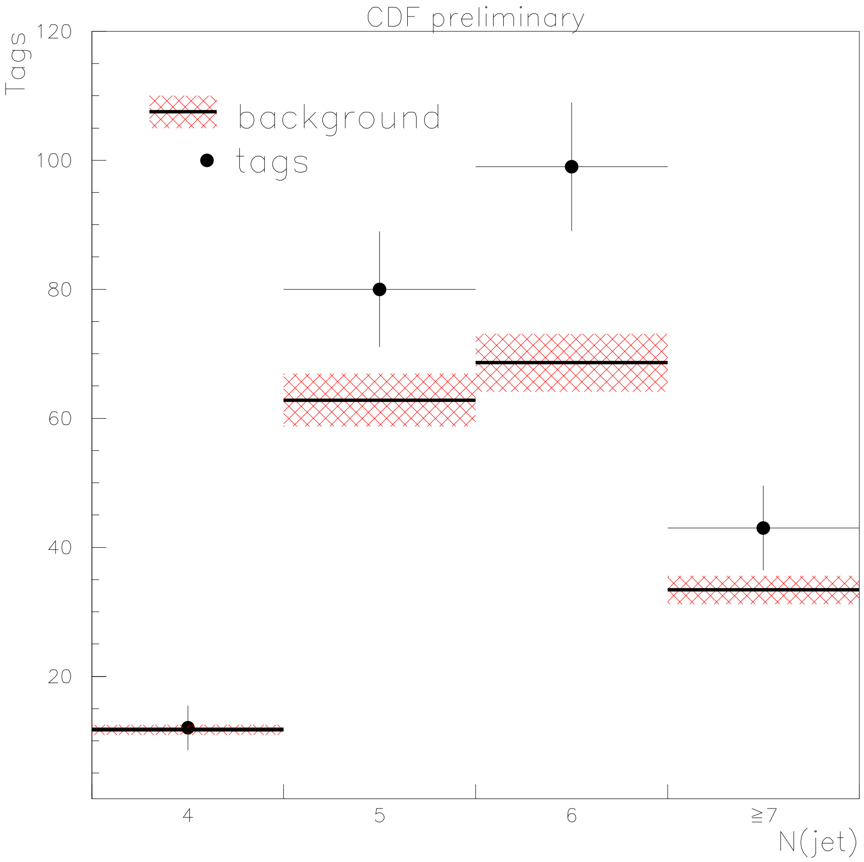
- QCD Multijet Production

Features:

- Signal-to-noise is $\approx \frac{1}{1000}$
- Additional cuts are required (b-tag, etc.).
- M_{Top} can be found if background is reasonable.

CDF All Jets

- **After all cuts including *b*-tag requirement**



All Jets Summary

Summary:

	DØ	CDF
Observed	15	192
Background	11 ± 2	137.1 ± 11.3
Expected	4.5 ± 0.5	26.6 ± 9.1
Expected evaluated at	M_{Top}= 170 GeV/c^2	M_{Top}= 175 GeV/c^2

All This Top...

The Tevatron has collected
a good amount of top:

- $\approx$ 13 Dilepton
- $\approx$ 70 Lepton + Jets
- $\approx$ 60 All jets

Enough to study basic properties:

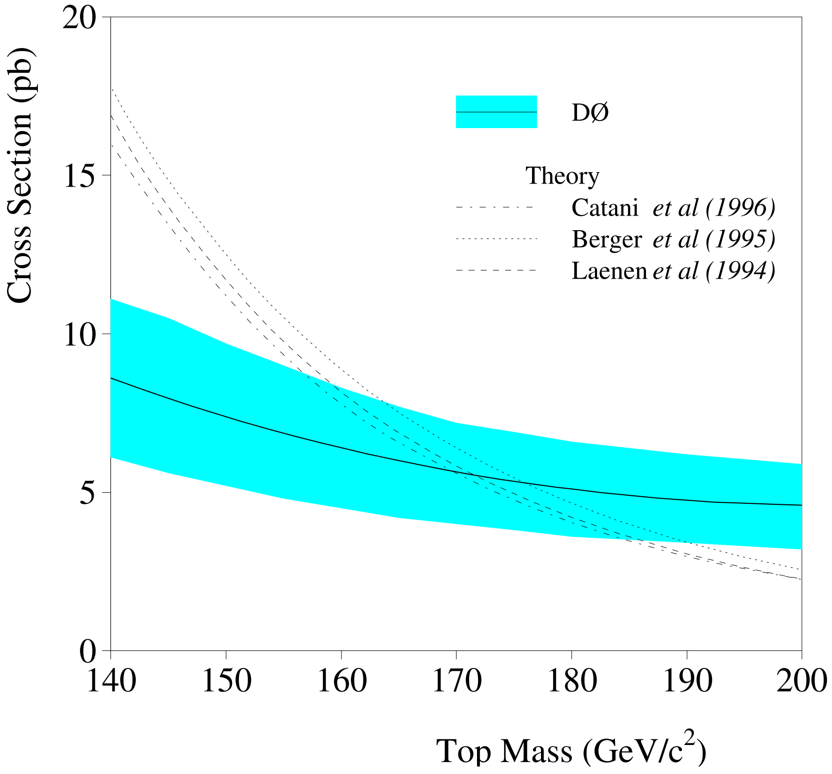
- $\sigma_{\bar{t}t}$
- M_{Top}
- V_{tb}
- Rare Decays

Cross Section

Straight forward:

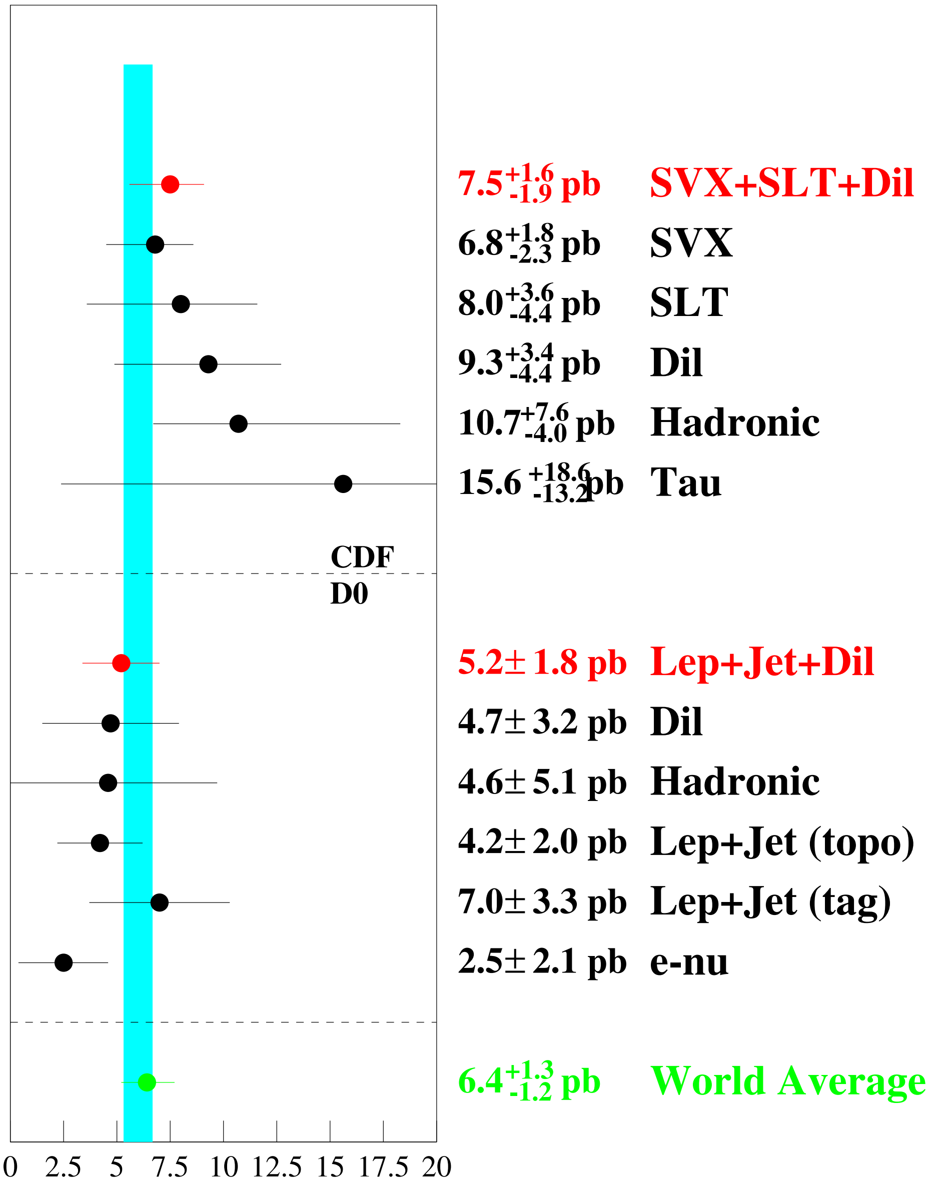
$$\sigma = \frac{N_{\rm obs} - N_{\rm bck}}{A \times \mathcal{L}}$$

- **A is the acceptance, and it varies with M_{Top}**



Cross Section Summary

- We can look at the cross section in each channel for both experiments:



Band is Laenen *et al* with calculated errors for M_{Top}= 170 GeV/c^2

The Top Quark Mass

- **Why?**
  - M_{Top} **is a standard model parameter.**
  - **Loop level interactions that can be measured depend, in part, on** M_{Top}**.**
  - $\lambda_t \approx 1$
- **The Tevatron has a lot of handles on it:**
  - **Lepton + Jets (CDF & DØ)**
  - **Dilepton (CDF & DØ)**
  - **All Hadronic (CDF)**

Fit Choices

Consider the following for good choice of fit procedure:

- Size of data sample (statistics)
- Small systematics
- Ability to separate background and signal in fit
- Small background

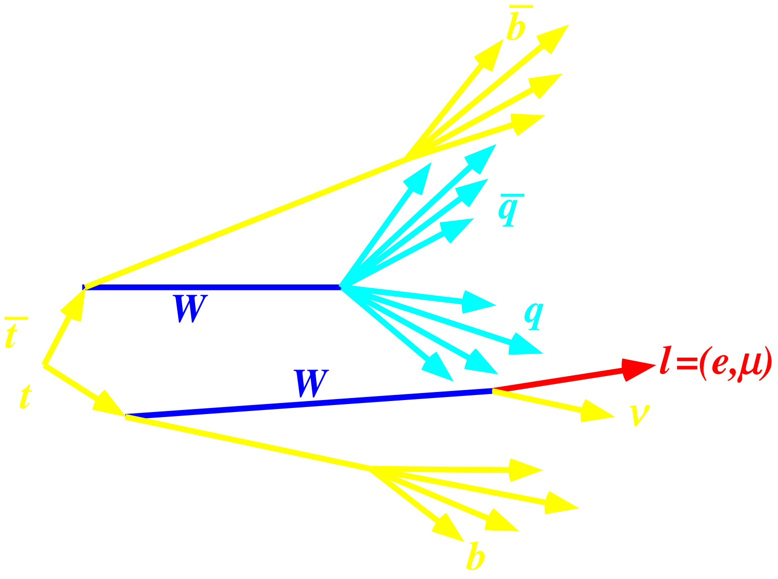
At the moment, the best fit is

Lepton + Jets 2-C Fit

- Both experiments have tried multiple methods on various samples.
- Answers stable.

Lepton + Jets

- Best channel
- Direct reconstruction from decay products:



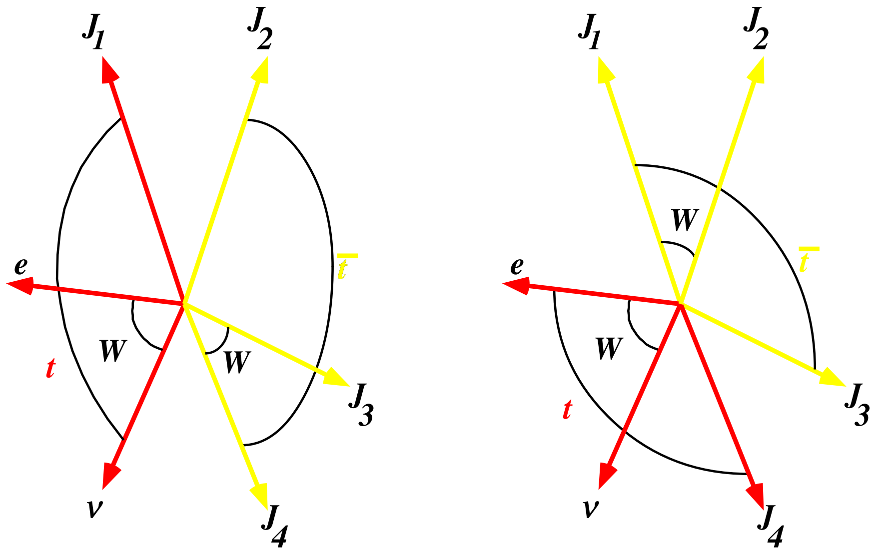
- Using constraints
  - $m(\ell\nu) = M_W$
  - $m(jj) = M_W$
  - $m(t) = m(\bar{t})$
- A 2-C kinematic fit.

Cuts and Procedure

Jet Assignment

Difficulty is:

- Don't know *a-priori* which jet is which

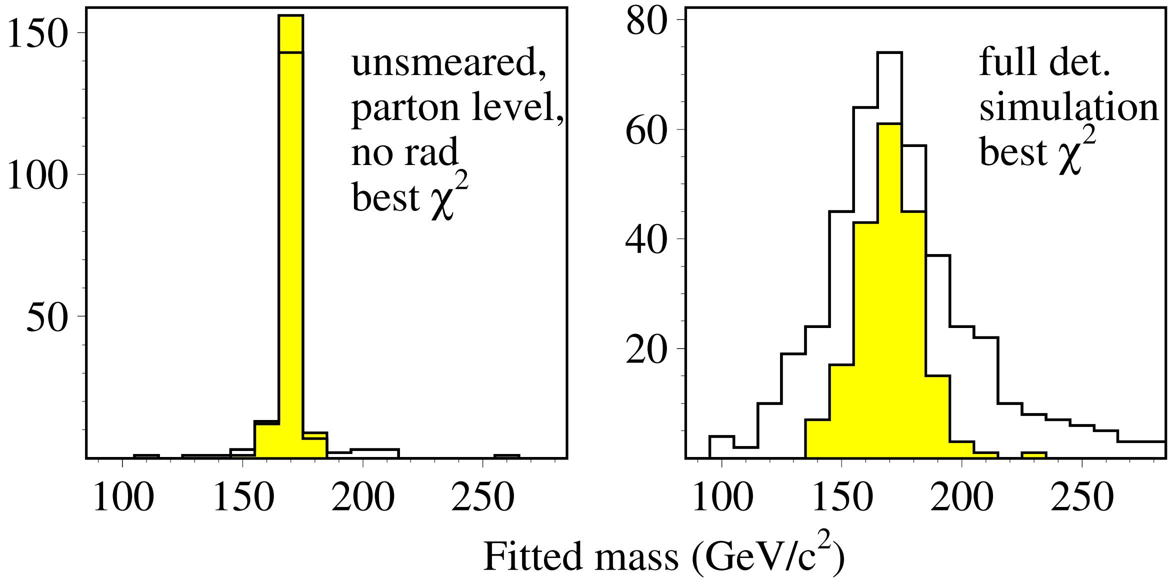


- There are 12 possible jet assignments
- p_z^ν can have two solutions
- 24 ways to fit for M_{Top}
  - One b-tag there are 12 ways
  - Two b-tags there are 4 ways

Jet Assignment and Radiation

- **Jet Radiation**
  - **Adds jets to the event**
  - **Reduces energy of measured jet**

- **Result is spread in M_{Top}'s peak.**



Correct Jet Combination

Extracting M_{Top}

The fitted mass is not M_{Top}

- **ISR and FSR**
- **Jet Misassignment**
- **Procedure Biases**

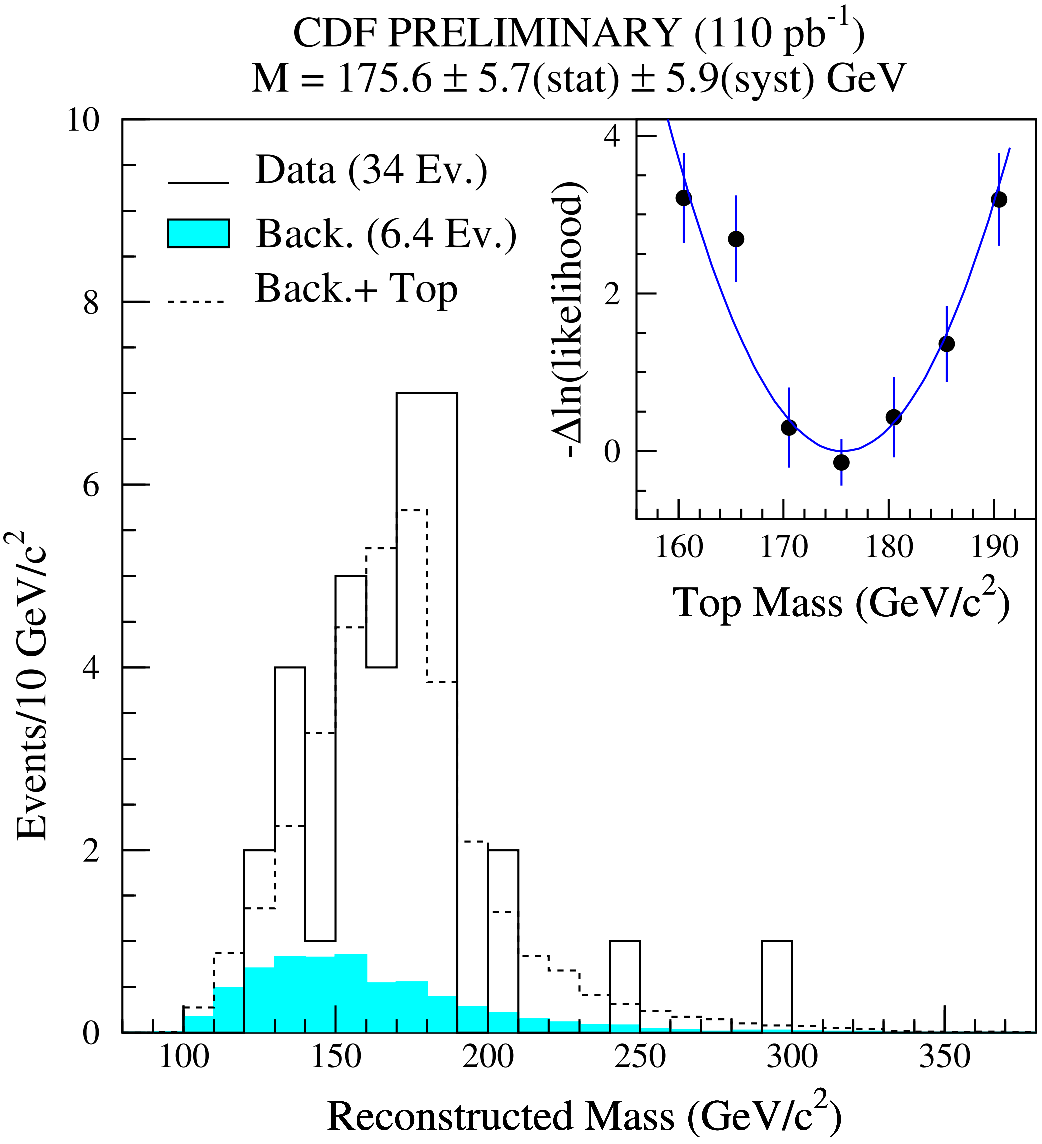
Use a series of Monte Carlo templates:

- **Background (W+Jets, QCD)**
- **$\bar{t}t$ Monte Carlo at different M_{Top}.**

And match the templates to the data.

- **Use log likelihood to match the data**

CDF M_{Top} Measurement



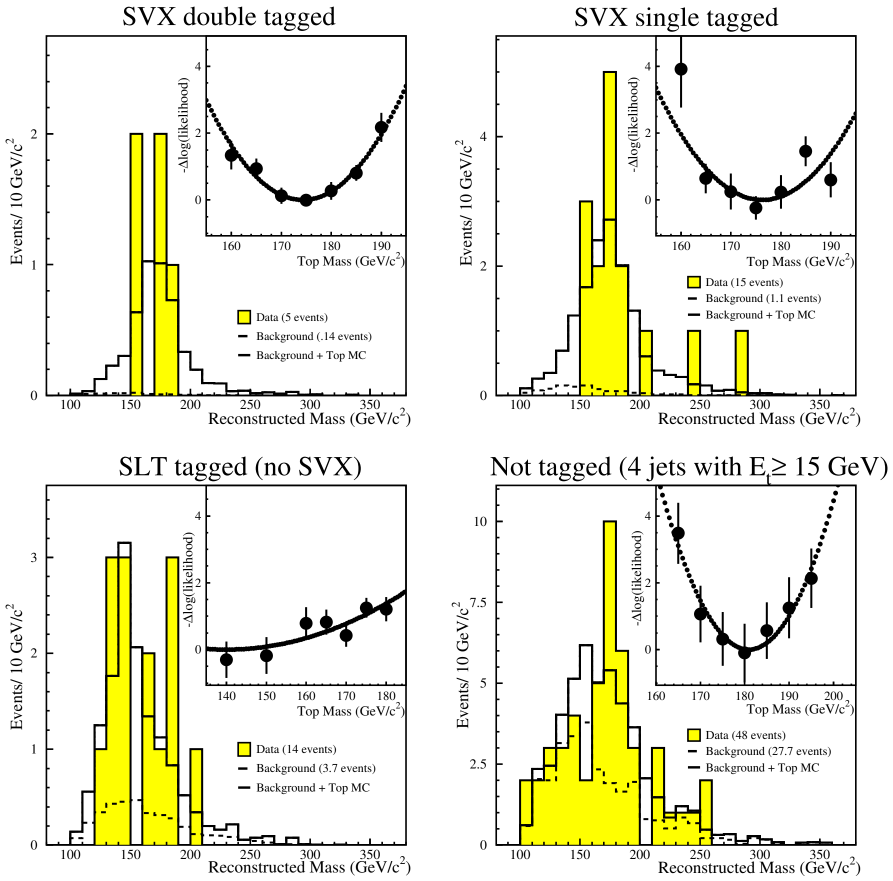
CDF PRELIMINARY (110 pb^{-1})
M = 175.6 ± 5.7(stat) ± 5.9(syst) GeV

Lepton + Jets

CDF Optimized M_{Top} Measurement

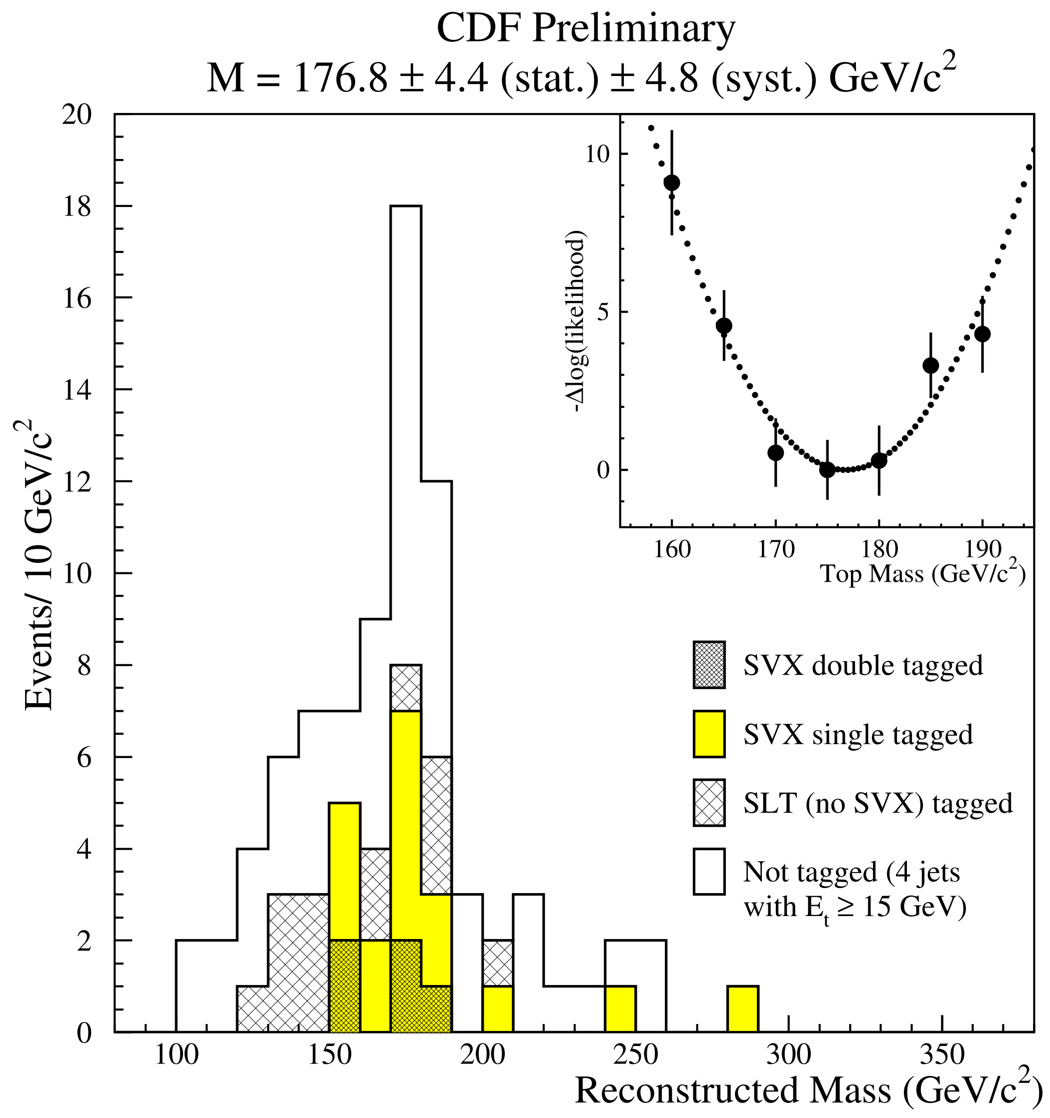
- Divide into 4 independent samples
  - SVX Double Tagged
  - SVX Single Tagged
  - Soft Lepton (no SVX) tagged
  - Not Tagged
- Fit each sample independently

CDF Preliminary



CDF Optimized M_{Top} Fit

- **Combine by likelihood**



DØ M_{Top}

DØ fits to both M_{Top} and a top-likelihood parameter, $\mathcal{D}$.

$\mathcal{D}$ is constructed from four variables:

- $\not{E}_{\mathrm{T}}$
- $\mathcal{A}$ **Background is planar, top is spherical**
- **Normalized H_T**

$$\frac{H_T - E_T^{\mathrm{j1}}}{H_{\|}}$$

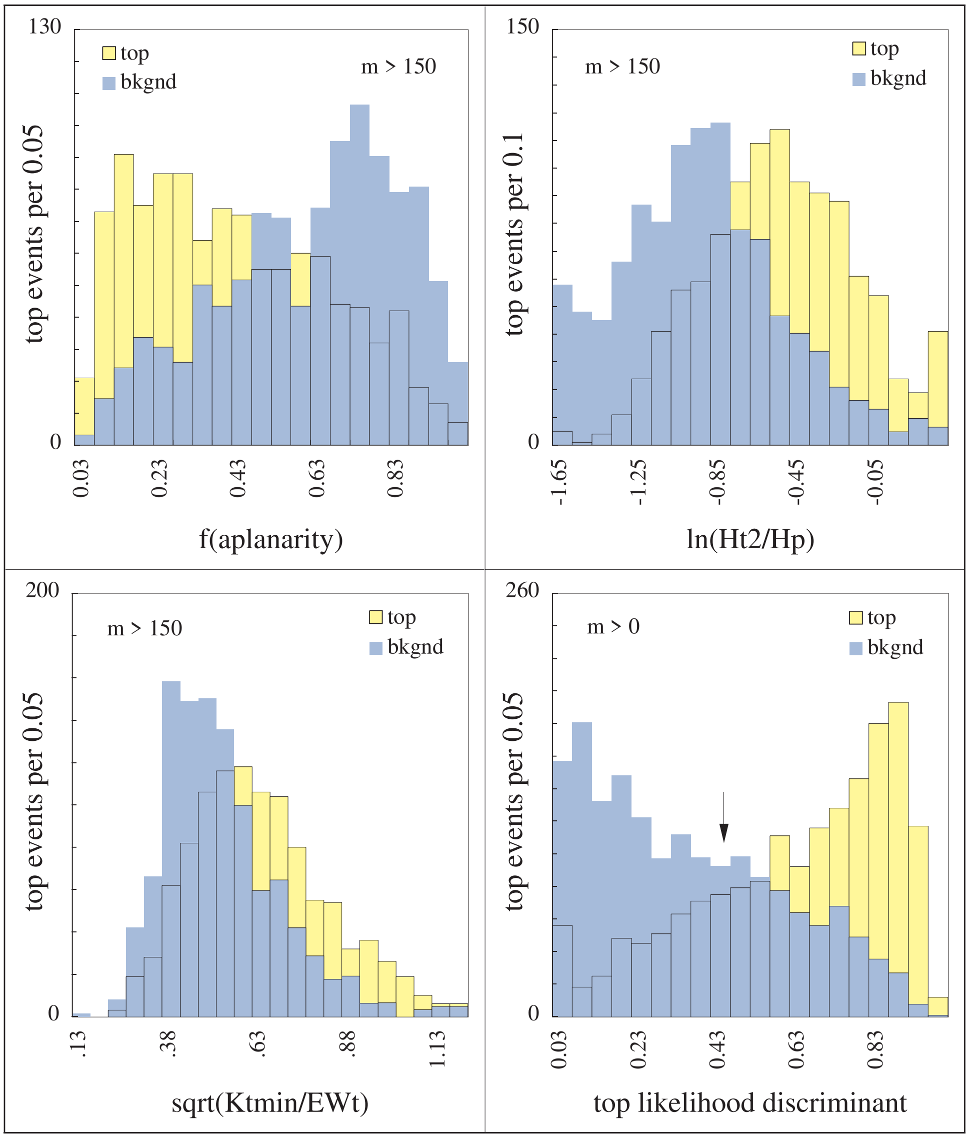
  Centrality

- **Jet Separation**

$$\frac{\mathrm{Min}(\Delta R_{jj})\dot{E}_T^{\mathrm{lesserjet}}}{E_T^W}$$

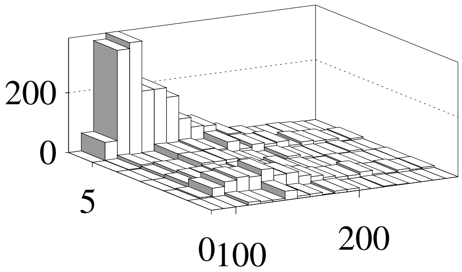
  Backgrounds have collinear jets

Combined such that there is little bias in M_{Top} as a function of $\mathcal{D}$.

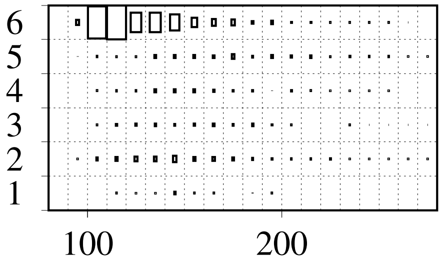

130
top
bkgnd
m > 150
top events per 0.05
0
0.03
0.23
0.43
0.63
0.83
f(aplanarity)
150
m > 150
top
bkgnd
top events per 0.1
0
-1.65
-1.25
-0.85
-0.45
-0.05
ln(Ht2/Hp)
200
m > 150
top
bkgnd
top events per 0.05
0
.13
.38
.63
.88
1.13
sqrt(Ktmin/EWt)
260
m > 0
top
bkgnd
top events per 0.05
0
0.03
0.23
0.43
0.63
0.83
top likelihood discriminant

$\mathcal{D}$

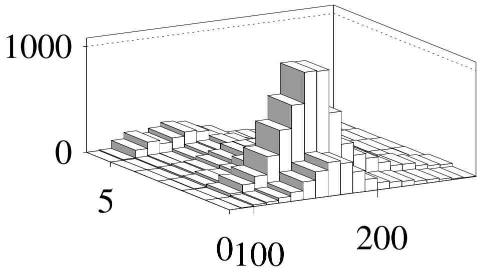
- **Separates signal and background**
  - **4-6 in $\mathcal{D}$ are background-like.**
  - **1-3 in $\mathcal{D}$ are top-like.**



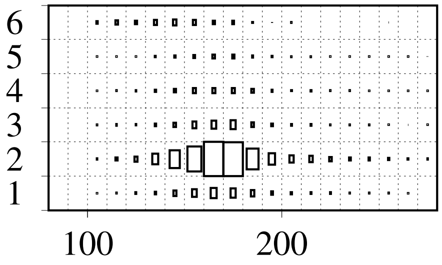
Background



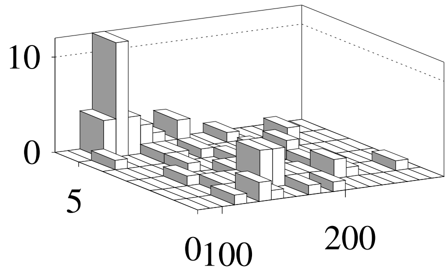
Background



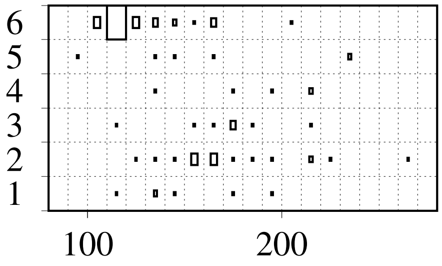
Herwig MC, m_t=170



Herwig MC, m_t=170



Data

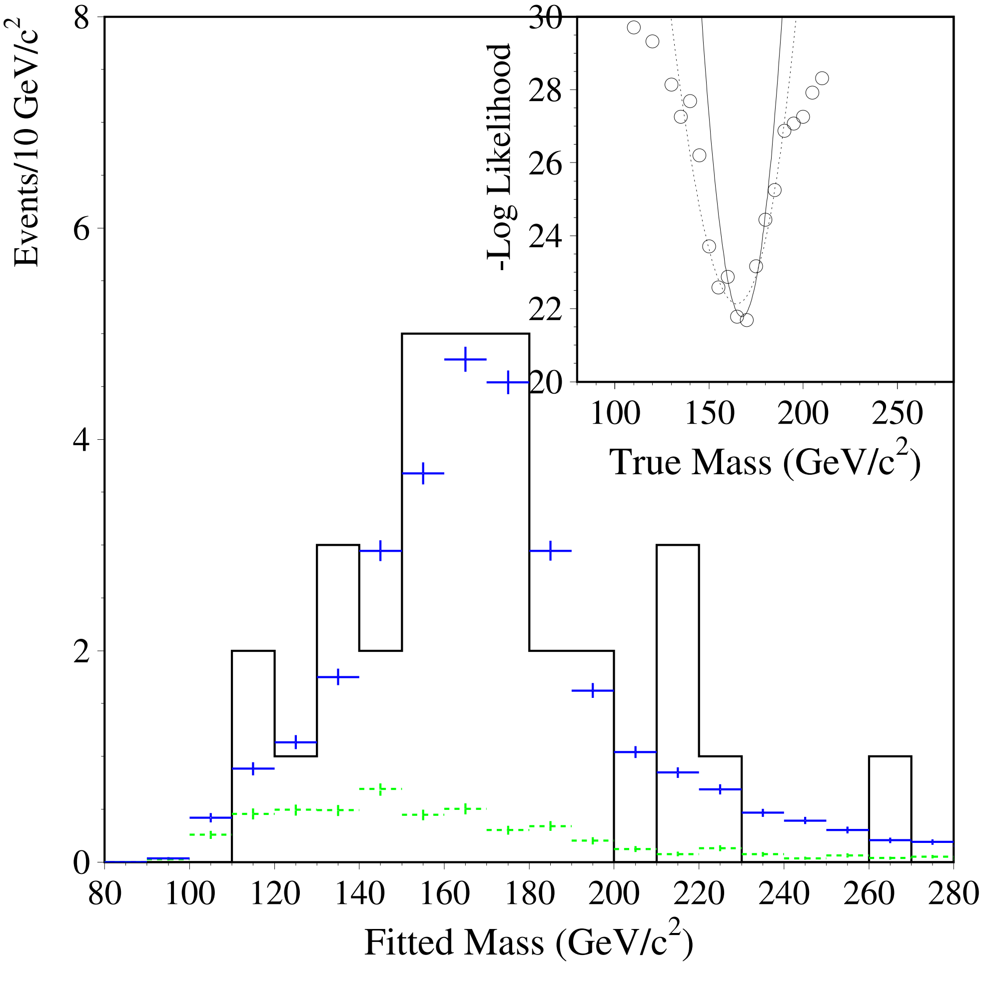


Data

DØ 2-D fit

$M_{Top} = 169 \pm 8$ **(stat) GeV/c^2**

32 events



Background

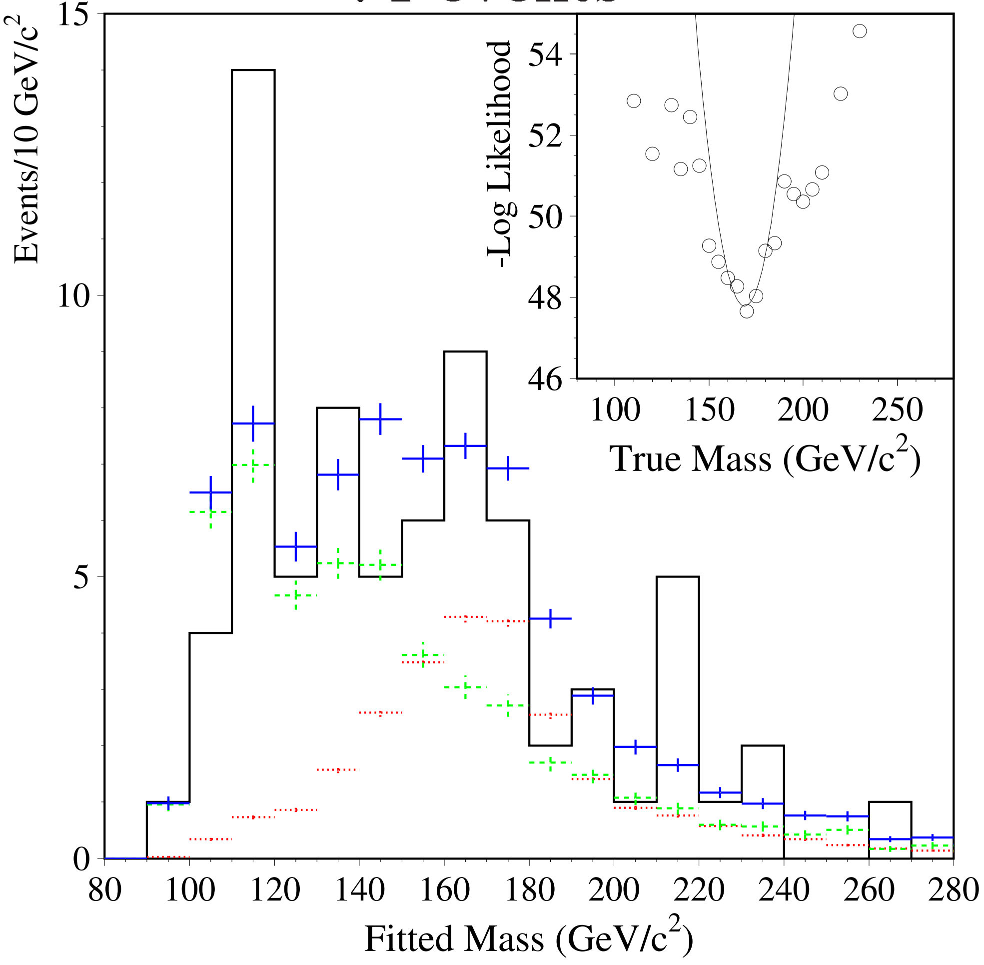
Background + Signal

PR Likelihood

List Likelihood bins Unconstrained fit:

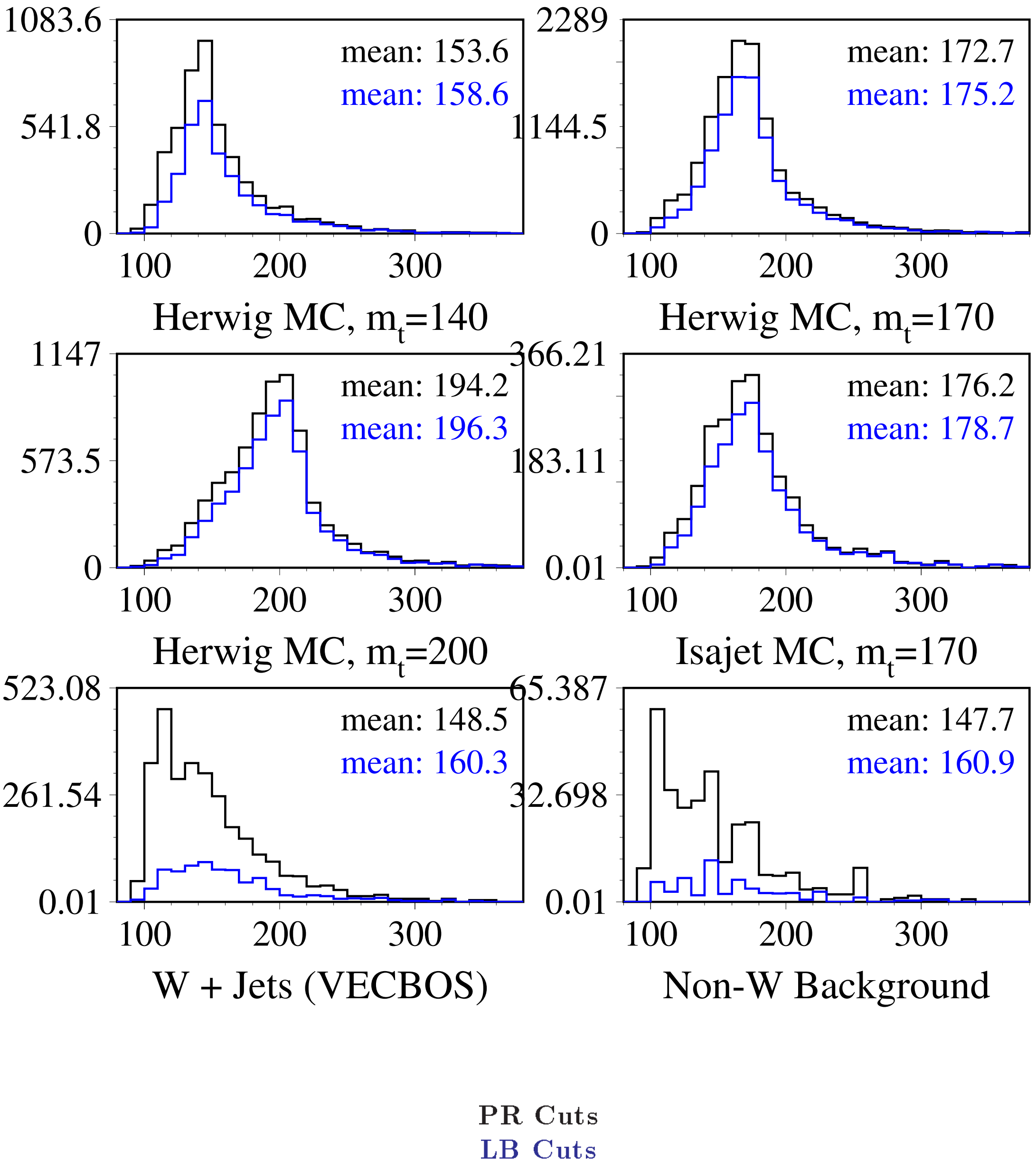
M_{Top}= 169 ± 10 (stat) GeV/c^2

74 events



Signal
Background
Signal + Background

No Fit Bias



Herwig MC, m_t=140

Herwig MC, m_t=170

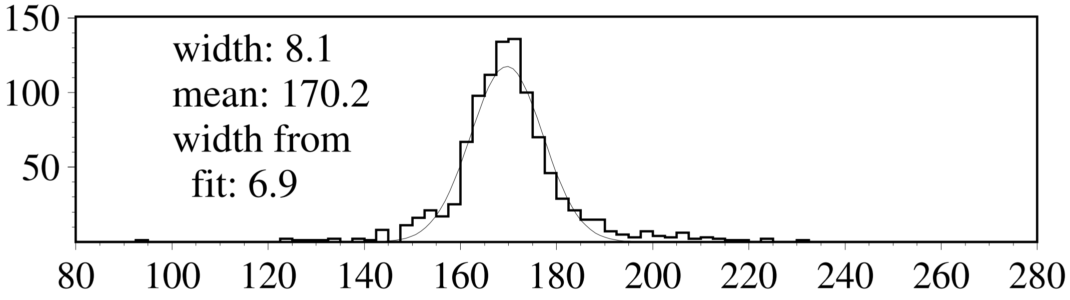
Herwig MC, m_t=200

Isajet MC, m_t=170

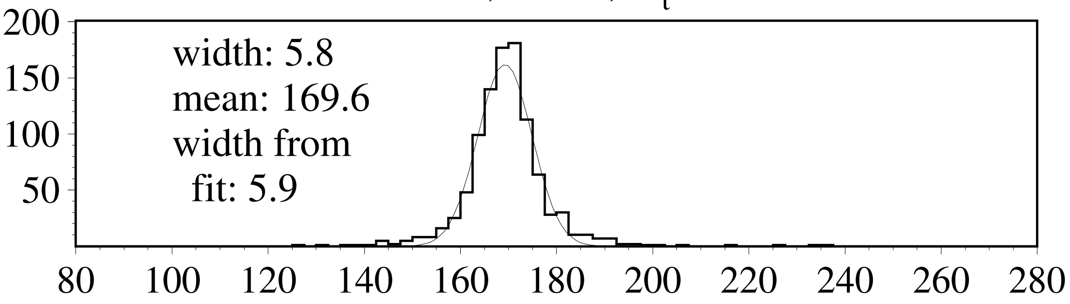
W + Jets (VECBOS)

Non-W Background

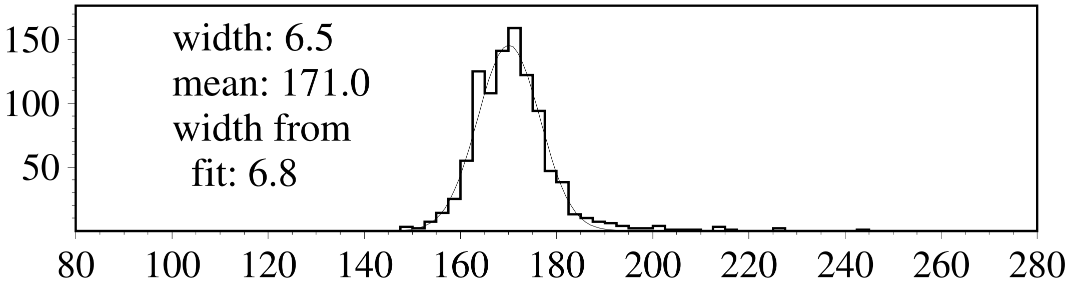
Ensemble Fits



PR cuts, 2D fit, m_t=170



NL cuts, 2D fit, m_t=170



NL cuts, 1D fit, m_t=170

Systematic Uncertainties

DØ

	Value (GeV/c^2)
Jet Energy Scale	7.3
Monte Carlo Model	4.3
Fitting Method	2.0
Total	8.0

M_{Top}= 169 ± 8 (stat) ± 8 (sys) GeV/c^2

CDF

	Value GeV/c^2
Soft Gluon + Jet E_T Scale	3.6
Different Generators	1.4
Hard Gluon Effects	2.2
Fitting Method	1.5
b-tagging Bias	0.5
Background Spectrum	0.7
Monte Carlo Statistics	0.8
Total	4.8

M_{Top}= 176.8 ± 4.4 (stat) ± 4.8 (sys) GeV/c^2

CDF's Good Fortune

- 4.4 GeV/c^2 error is found in the fit
- Monte Carlo indicates there is a 8.2% chance of observing a 4.4 GeV/c^2 error or less.
- MC studies indicate when a small error is returned by the fit, the deviation from M_{Top} is also small.
- If the hard radiation rate in the MC is reduced the probability rises to 15%.
- If $n_{background}$ is not constrained, the probability increases to 39%.

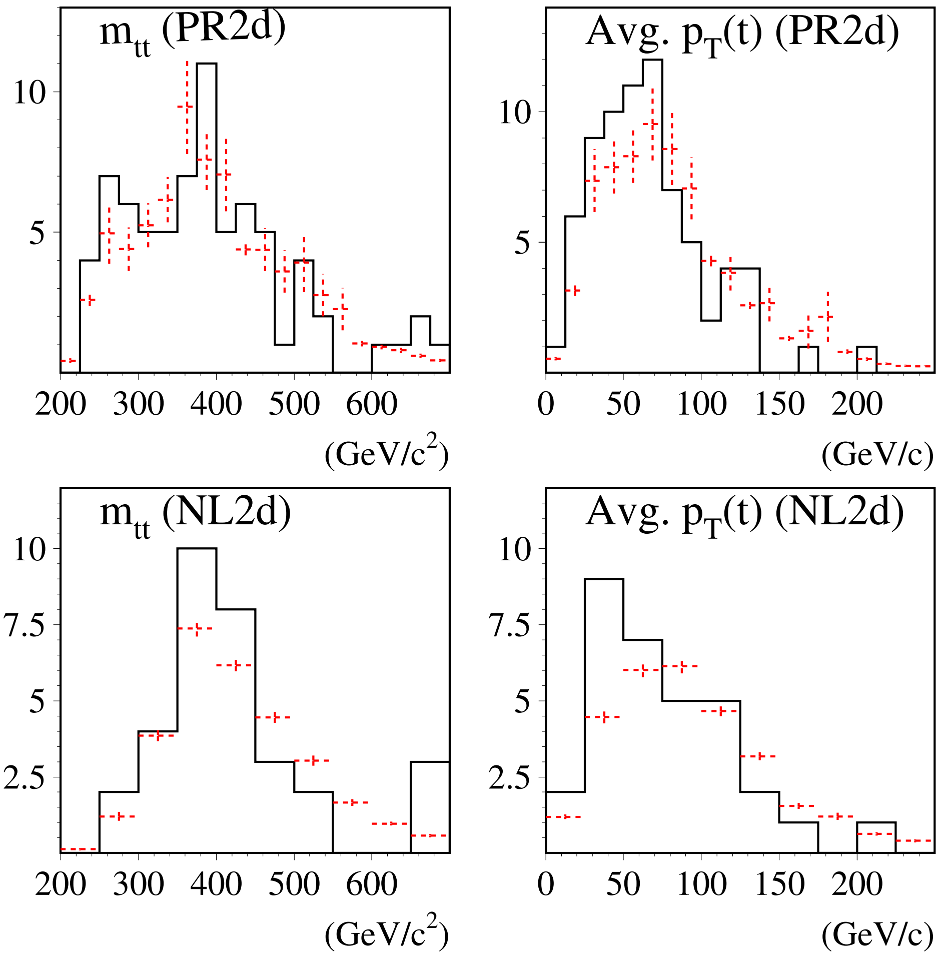
Combining CDF and DØ M_{Top}

- Only Lepton + Jets
  - CDF: 176.8 ± 4.4 ± 4.8 GeV/c^2
  - DØ: 169 ± 8 ± 8 GeV/c^2
- Conservative assumption that all systematic errors are 100% correlated, except:
  - Jet energy scale,
  - b-tagging bias, and
  - Monte Carlo statistics
- Central value found by weighting by statistical error only.

M_{Top}= 175.0 ± 3.9 ± 4.5 GeV/c^2

Production Kinematics

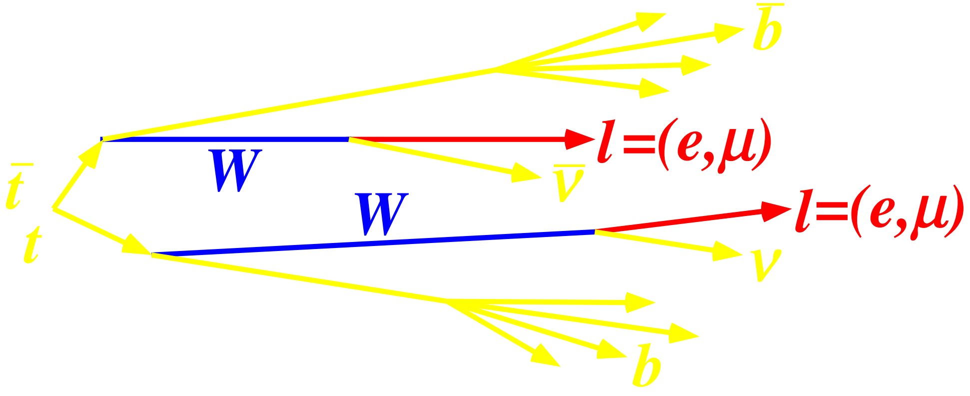
- $M_{\bar{t}t}$ **and** $p_T^{\bar{t}t}$ **of the** $\bar{t}t$ **system**



Data

Monte Carlo

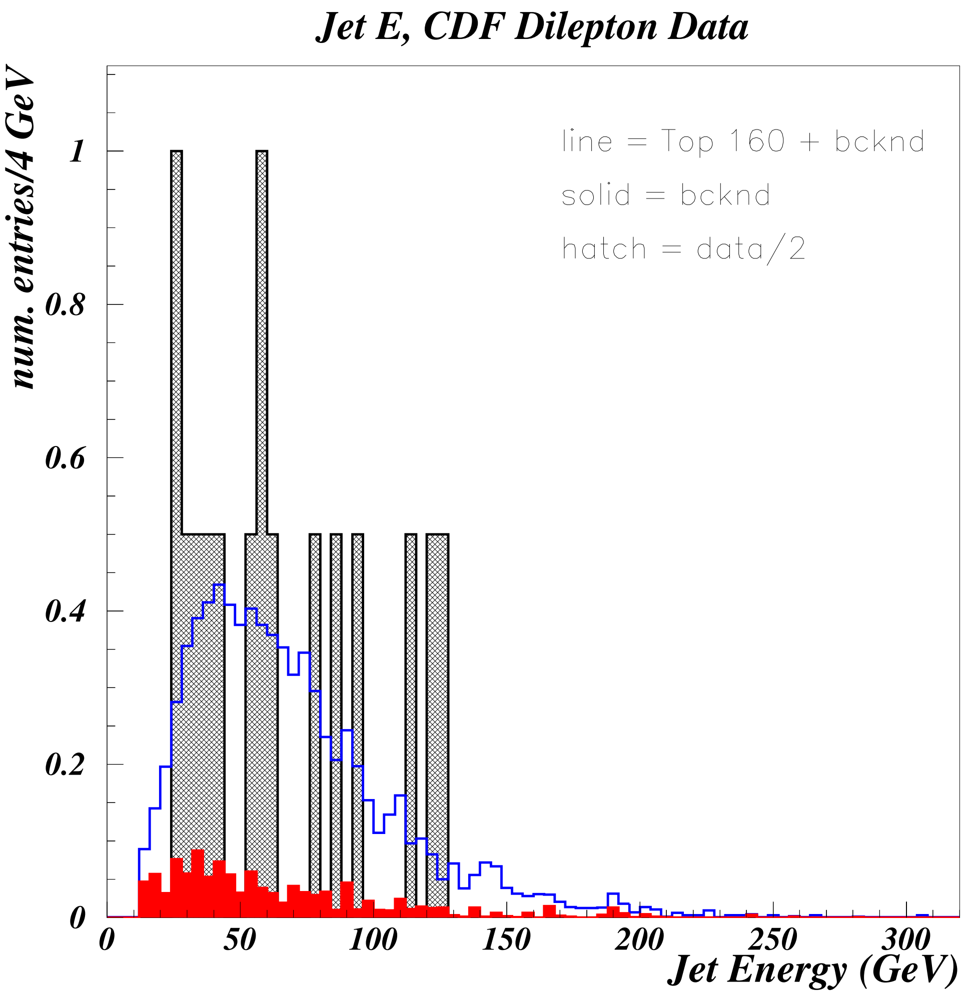
Dilepton M_{Top}



- **Two neutrinos**
- **Must make an assumption**
  - **CDF matches jet E spectra to MC.**
  - **DØ calculates a weight function *vs* M_{Top}.**

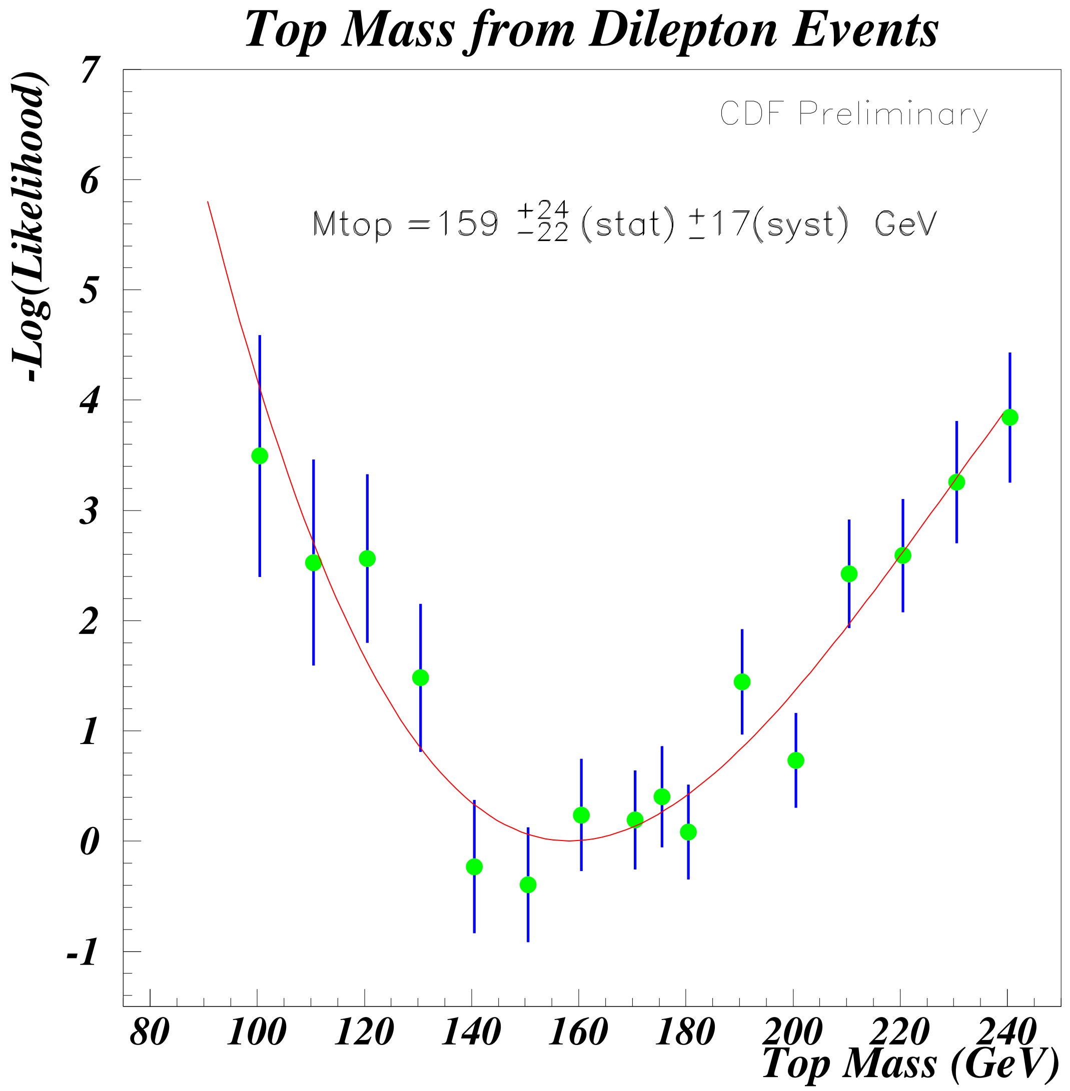
Dilepton M_{Top} - CDF

- **Match E distributions of highest two E_T jets**
- **8 events are fit**
  - $H_T >$ **170 GeV**



Dilepton M_{Top} - CDF

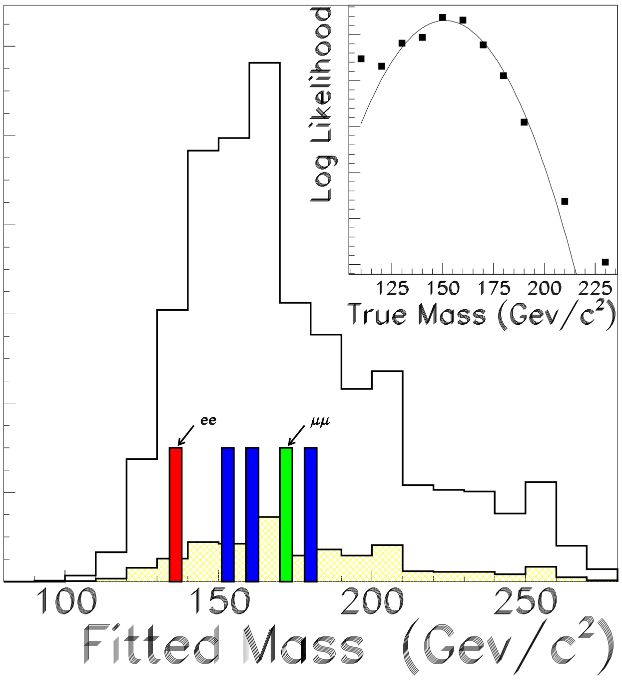
- **Likelihood fits to top and background distributions.**



Top Mass from Dilepton Events

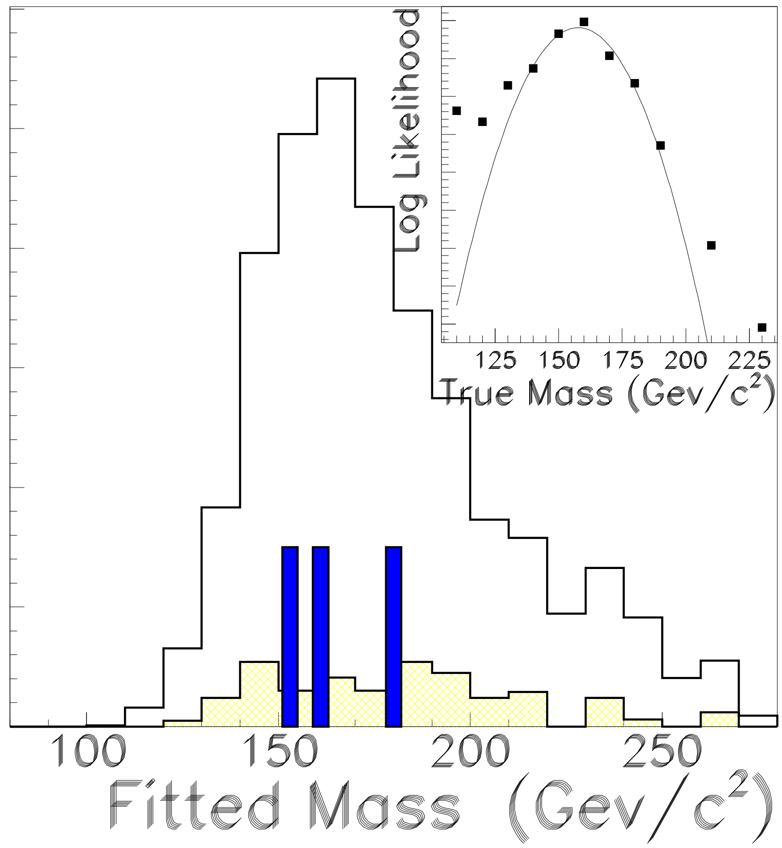
Dilepton M_{Top} - DØ

- **Based on a method by Kondo, Dalitz, and Goldstein**
- **Form weight function from**
  - **Parton distribution functions**
  - **Lepton energies**
- **Use all three dilepton channels (ee, $e\mu$, $\mu\mu$):**
  - **5 events**
  - 1.57 ± 0.4 **background**
- M_{Top}**= 151±21 (stat) ±10 (sys) GeV/c^2**

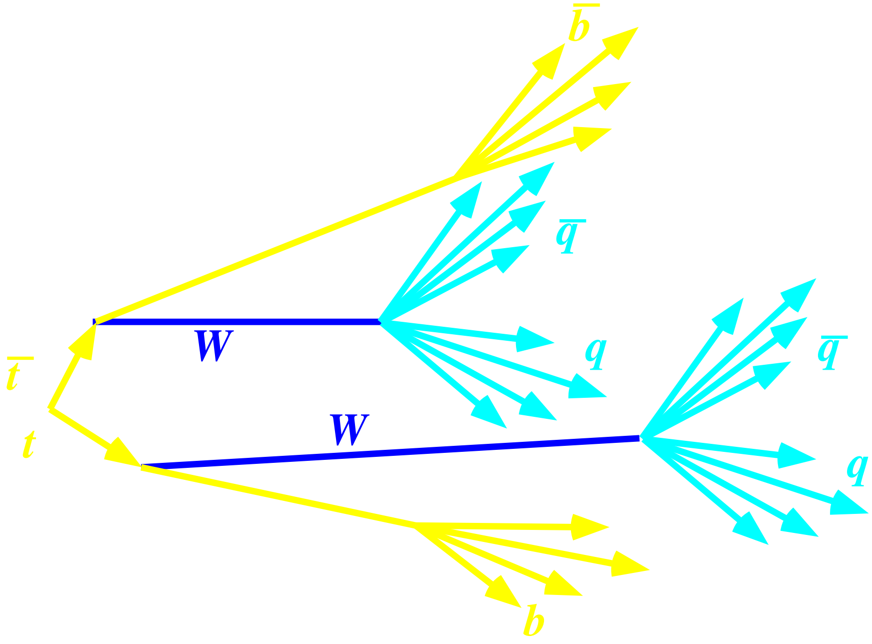


Dilepton M_{Top} - DØ

- **Use only the $e\mu$ channel**
  - **3 events**
  - 0.36 ± 0.09 **background**
- M_{Top}= 158±24 **(stat)** ±10 **(sys) GeV/c^2**



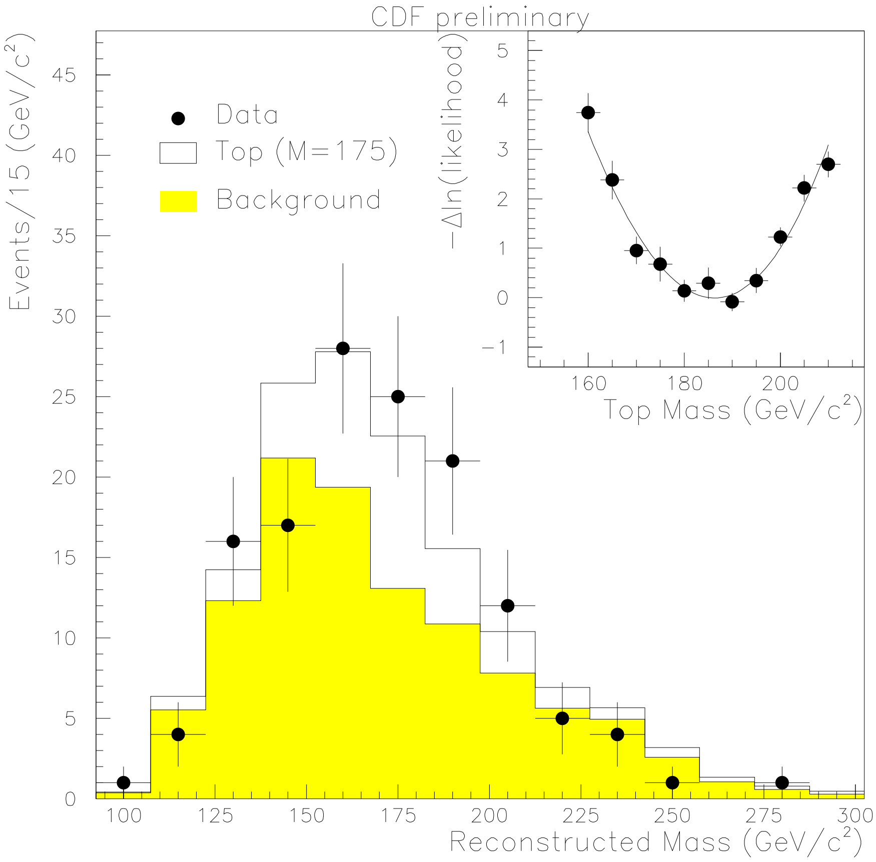
All Hadronic M_{Top}



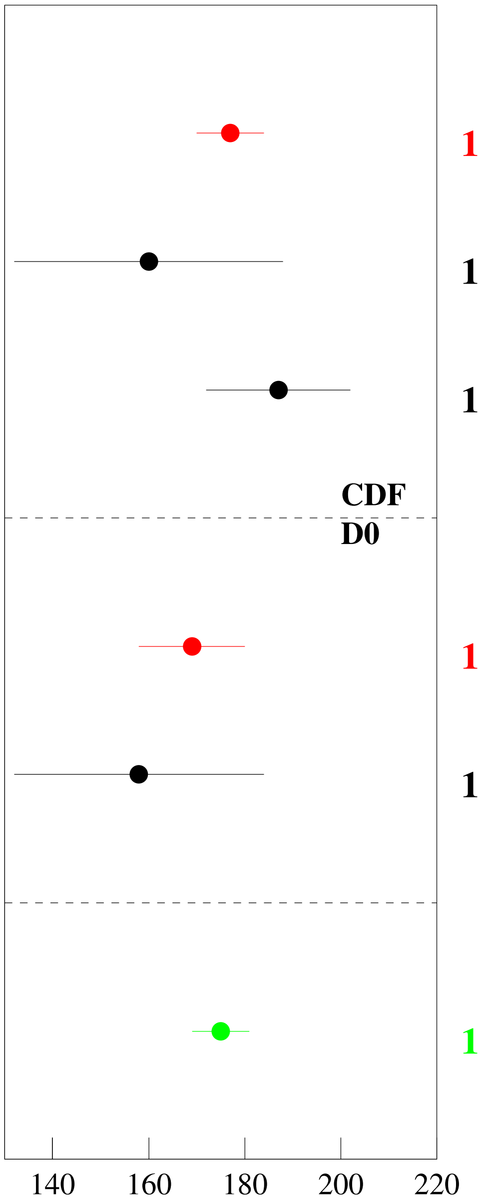
- CDF only.
- 3-C fit
- Require events to be double-tagged.

All Hadronic M_{Top} - CDF

- M_{Top}= 187 ± 8 (stat) $^{+13}_{-12}$ GeV/c^2



M_{Top} Summary



177 ± 7 GeV/c^2 Lep+Jet

160 ± 28 GeV/c^2 Dil

187 ± 15 GeV/c^2 Hadronic

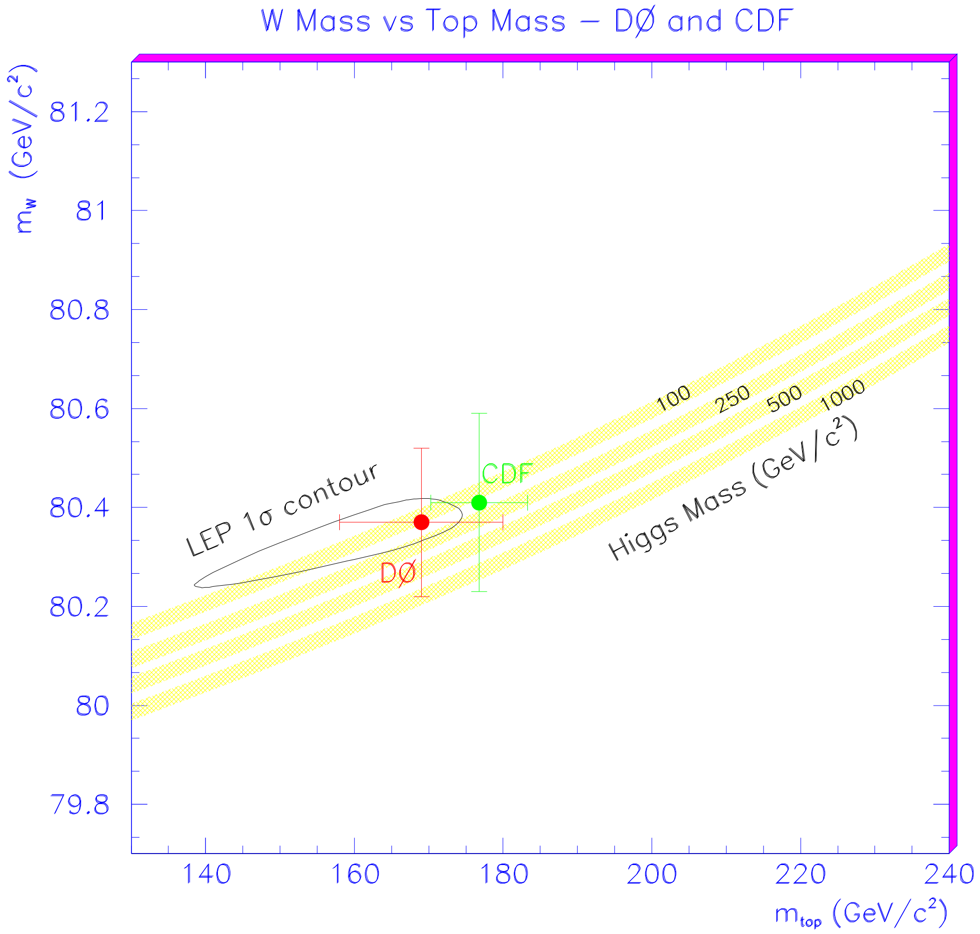
169 ± 11 GeV/c^2 Lep+Jet

158 ± 26 GeV/c^2 Dil

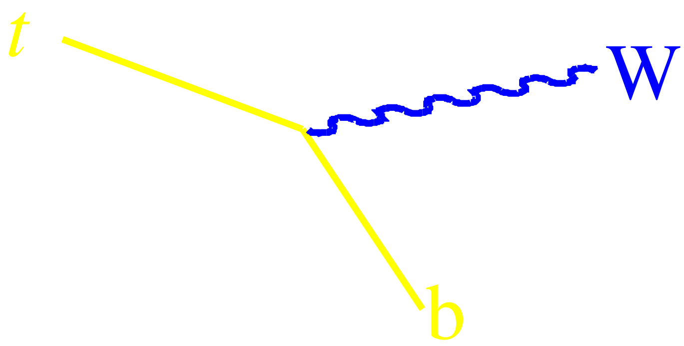
175 ± 6 GeV/c^2 World Average

M_W and M_{Top}

$$M_T = \mathbf{175 \pm 6\ GeV/c^2}$$
$$M_W = \mathbf{80.35 \pm 0.13\ GeV/c^2}$$



V_{tb} - CDF



- $V_{tb} \approx 1$ in a 3-Generation SM (Unitarity)
- Look at lepton + jets and dilepton samples
  - Measure ration of events with 0, 1, and 2 b-tags
  - Extract

$$b = \frac{\mathrm{BR}(t \to Wb)}{\mathrm{BR}(t \to WX)}$$

  - Result is independent of
    - $\sigma_{\bar{t}t}$
    - $\frac{\mathrm{BR}(W\to\ell\nu)}{\mathrm{BR}(W\to\bar{q}q)}$

V_{tb} - CDF

- **Combine all information using a maximum likelihood**

$$b = 0.94 \pm 0.27(\mathrm{stat}) \pm 0.13(\mathrm{sys})$$

b > 0.34 at 95% C.L.

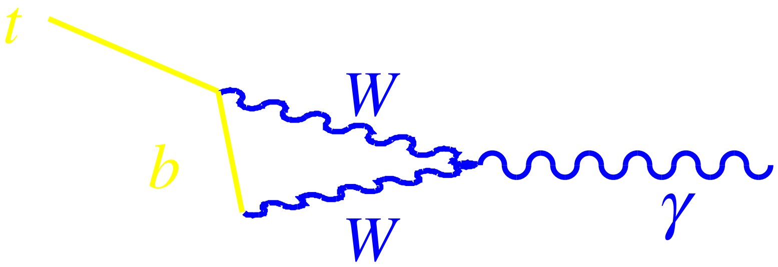
- **Assume 3-generation unitarity to find**

$$|V_{tb}| = 0.97 \pm 0.15 \pm 0.07$$

$$|V_{tb}| > 0.5895\%\mathrm{C.L.}$$

Rare Decays

- Look for $\bar{t}t$ events with
  - One t decays by the SM ($t \to Wb$)
  - Second by a rare decay:
    - $* \; t \to \gamma(c, u)$
    - $* \; t \to Zc$
    - $* \; t \to WZb$



- CDF has done an initial search for $t \to \gamma q$:

$$\mathbf{BF}(t \to c\gamma) + \mathbf{BF}(t \to u\gamma) < \mathbf{2.9}\ \%$$

(95% C.L.)

Future

We have lots of top, but looking forward:

- Tevatron Run II
- Tevatron Run III (TeV33)
- LHC

Tevatron Upgrades

- **Run I** (1992-1996)
  - 100 pb^{-1} Integrated Luminosity
- **Run II** (scheduled 1999-??)
  - Center of Mass Energy up from 1.8 TeV to 2.0 TeV.
  - 2 fb^{-1} Integrated Luminosity
- **Run III** (TeV33)
  - Planning and Evaluating
  - Run between Run II and LHC
  - up to 30 fb^{-1} Integrated Luminosity

Detector Upgrades

- **Run II**
  - New Inner Tracking System
    - Improved b-tag efficiency
    - b-tagging efficiency as high as 40% per b.
    - Increased coverage for e and μ id.
  - DØ will get a 2T magnetic field.
  - CDF has improved forward calorimeter capability
  - High speed electronics and better triggers.

Top Physics

- Top cross section goes up 40% with the increase in Tevatron energy (1.8 TeV → 2.0 TeV).
- Then, for $M_{Top} = 170$ GeV/c^2
  - Signal-to-background: 5:1 (2:1 in Run I)

	Run 2	Run 3 (TeV33)
$\bar{t}t \rightarrow \ell\ell$	200	$\approx$ 3,000
$\bar{t}t \rightarrow \ell +$ 4 jets	1,800	$\approx$ 27,000
single top	330	5,000
$\sigma_{\bar{t}t}$ Error	$\approx$ 8%	$\approx$ 6%
M_{Top} Error	$\approx$ 3 GeV/c^2	$\approx$ 1 GeV/c^2

Future Top Physics

- Top Mass
  - Top mass to 3 GeV/c^2 and W mass to 50 MeV
    - → Higgs mass to ≈ 80% of itself
- Top Cross Section
  - Search for excess
  - Search for resonances
- Single Top Production
  - $\sigma(\bar{p}p \to t + X)$ to ≈ 19%
  - $\Gamma(t \to Wb)$ to ≈ 25%
- V_{tb}
  - Measure V_{tb} to ≈5 %.
  - Test for three or more generations in SM

LHC – CMS & ATLAS

- Top is *really* a background.
- 6000 $\bar{t}t$ pairs produced a day.
- 100 cleanly reconstructed lepton + jet events
- 10 isolated $e\mu$ pairs a day
- Enable a broad range of top studies
  - M_{Top} to 0.5 GeV in the dilepton channel
  - V_{tb} to 5%
  - Rare decay searches ($t \to Zc$, $t \to Ws$, $t \to Wd$, etc).
- Gluon radiation will be a problem

One Page Summary

- Cross section:

DØ	**5.2 ± 1.8 pb**
CDF	**7.5** $^{+1.9}_{-1.6}$ **pb**
World Average	**6.4** $^{+1.3}_{-1.2}$ **pb**

- Mass:

CDF (Lepton+Jets)	**177 ± 7 GeV/c**^{2}
DØ(Lepton+Jets)	**169 ± 11 GeV/c**^{2}
CDF (Dilepton)	**162 ± 22 GeV/c**^{2}
DØ(Dilepton)	**158 ± 28 GeV/c**^{2}
World Average	**175 ± 6 GeV/c**^{2}

- Rare Decays:
  - **CDF has shown** $t \rightarrow \gamma q$ **is less than 2.9% (95 % CL)**
- V_{tb}
  - **CDF has shown** $|V_{tb}| > 0.58$ **(95% CL).**

Conclusions

- **In the two years since the top discovery we have done a lot.**
  - **Collected a sample of 140 top events**
  - $\sigma_{\bar{t}t}$ **to 20% of itself**
  - M_{Top} **to 5% of itself**
- **From here..**
  - **Tevatron Run II**
    - **Significant improvements in** M_{Top} **and** $\sigma_{\bar{t}t}$
    - **Better measurements of rare decays and CKM elements.**
  - **Tevatron Run III**
  - **LHC**
    - **Top Factory**

Conclusions

$$M_T = \mathbf{175 \pm 6\ GeV/c^2}$$
$$M_W = \mathbf{80.35 \pm 0.13\ GeV/c^2}$$