Top Quark Physics

(Lecture II)

Jianming Qian
The University of Michigan

Outline

- **Production and decays**
- **Pair production cross section**
- **Top quark mass**
- **Event kinematics**

China Center of Advanced Science & Technology
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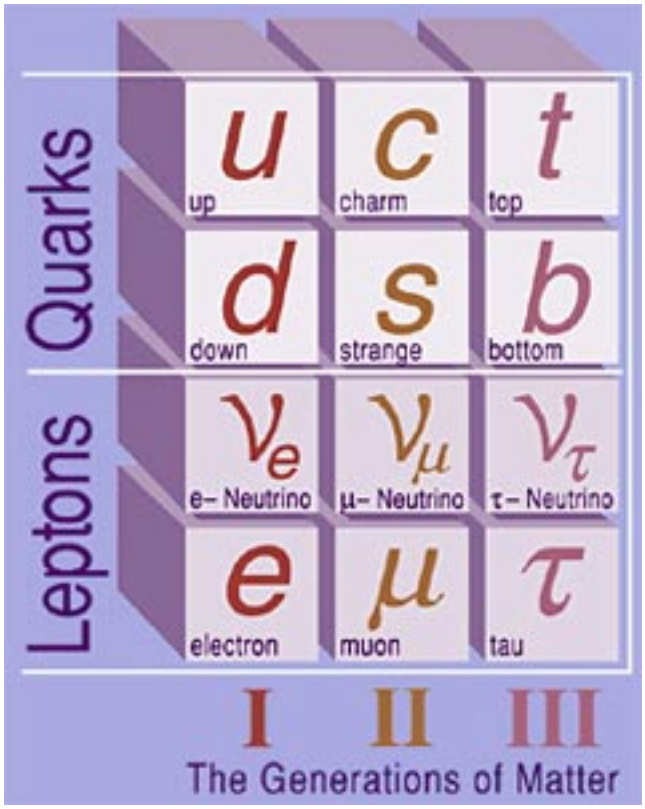
Building Blocks of Matter



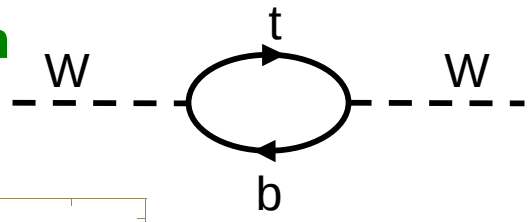
- **1975 – discovery of the τ lepton**
  Perl et al, PRL 35, 1489 (1975)
- **1977 – discovery of the b quark**
  Herb et al, PRL 39, 252 (1977)
  - **weak isospin = -0.504**
  - **no flavor changing neutral current**
  - **need weak isospin partner**
- **1995 – discovery of the top quark**
  CDF, PRL 74, 2626 (1995)
  DØ, PRL 74, 2632 (1995)
- **2000 – observation of tau neutrinos**

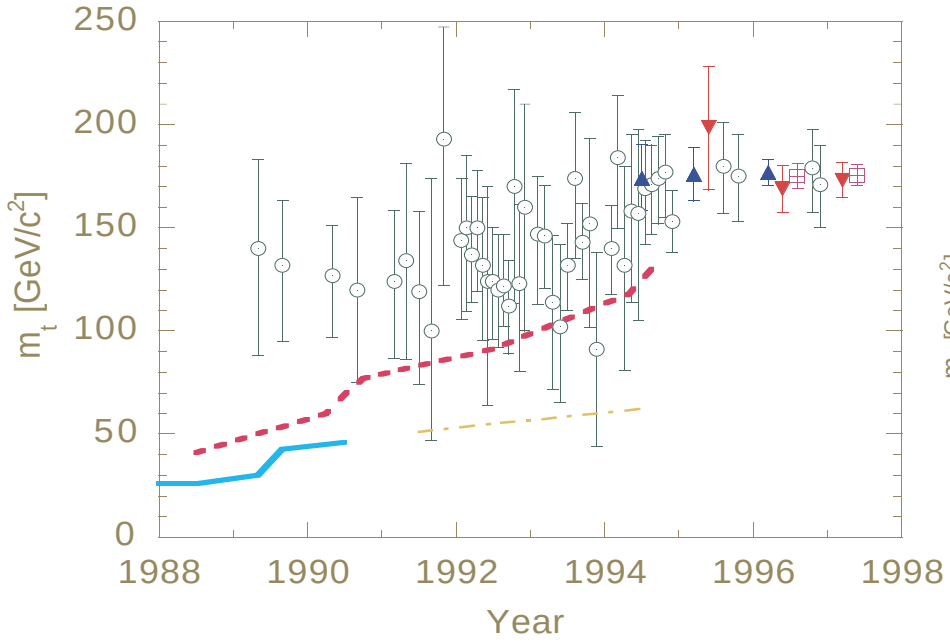
Hunt for the Top Quark

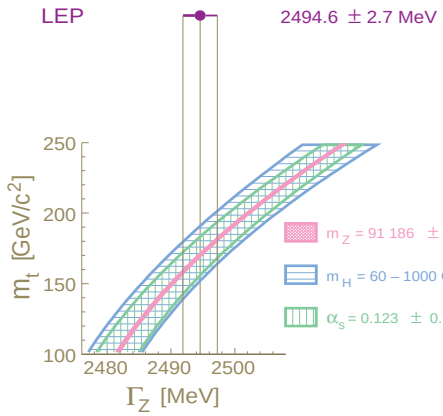
Direct searches at colliders

1979-84	PETRA (DESY)	e^+e^-	m_{top}>23.3 GeV
1987-90	TRISTAN (KEK)	e^+e^-	m_{top}>30.2 GeV
1989-90	SLC (SLAC) LEP (CERN)	e^+e^-	m_{top}>45.8 GeV
1990	SppS (CERN)	pp	m_{top}>69 GeV
1991	Tevatron (FNAL)	pp	m_{top}>77 GeV
1992	Tevatron (FNAL)	pp	m_{top}>91 GeV
1994	Tevatron (FNAL)	pp	m_{top}>131 GeV

Indirect constraints from radiative corrections

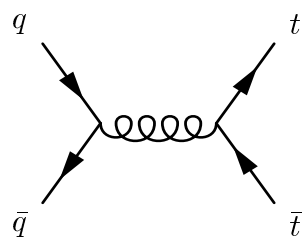




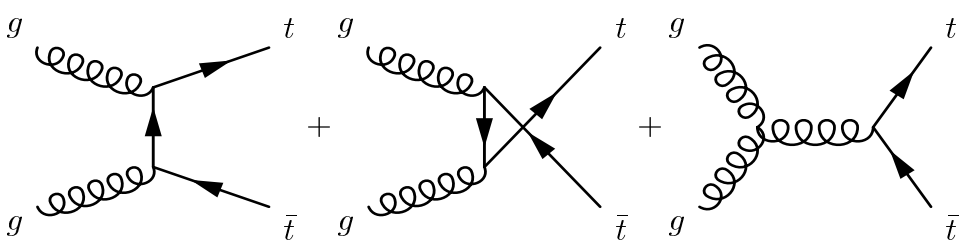


Top Quark Production

Top-antitop quark pair production

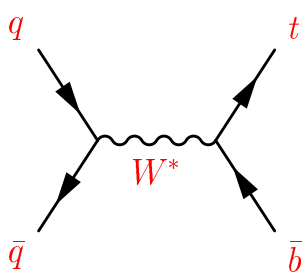


$q\bar{q} \to t\bar{t}$

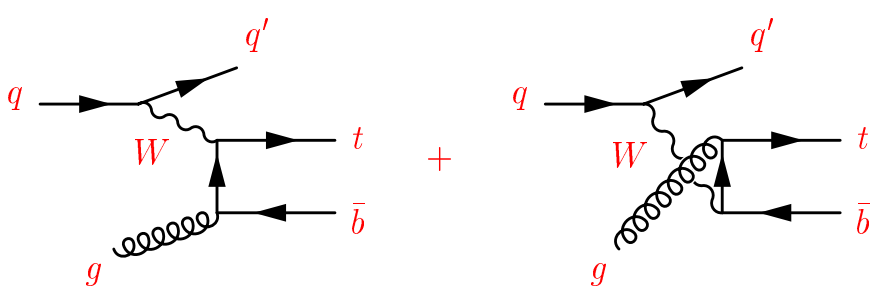


$gg \to t\bar{t}$

Single top quark production



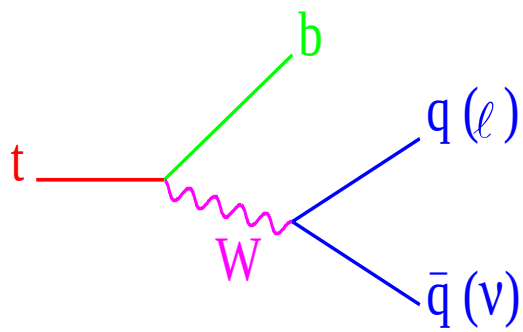
$q\bar{q} \to t\bar{b}$



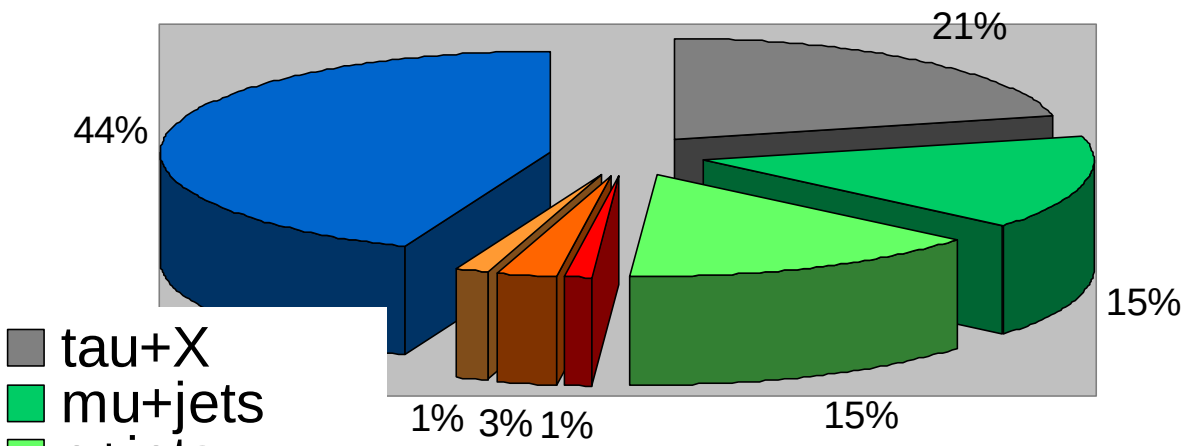
$qg \to q' t\bar{b}$

Top Quark Decay

In the standard model,
the top quark is short lived and decay almost exclusively to W and b quark



$$(W \to \ell\nu, W \to \ell\nu) \Rightarrow \ell\ell$$
$$(W \to \ell\nu, W \to qq') \Rightarrow \ell + \text{jets}$$
$$(W \to qq', W \to qq') \Rightarrow \text{All-jet}$$

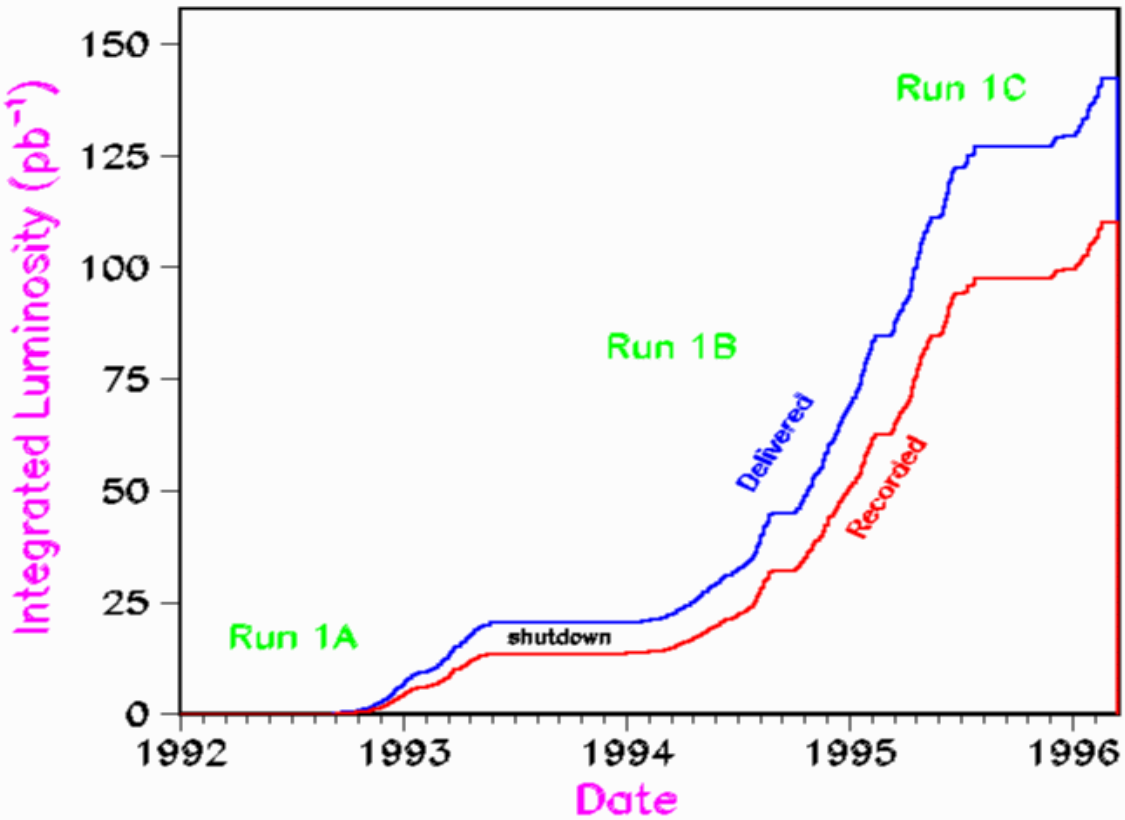


$\ell = e, \mu$

$$t\bar{t} \Rightarrow$$
$$(\ell\nu\bar{b})(\ell\nu b) \to \ell\ell' j^2 \not{E}_T$$ **Dilepton**
$$(\ell\nu\bar{b})(q\bar{q}'b) \to \ell j^4 \not{E}_T$$ **Lepton+jets**
$$(q\bar{q}'\bar{b})(q\bar{q}'b) \to j^6$$ **Alljets**

Data Sample

- **Tevatron Run I (1992–1996):**
  accumulated ~120 pb^{-1} integrated luminosity at a center-of-mass energy of 1.8 TeV



- **Tevatron Run II (2001–2006):**
  expect to accumulate ~20 fb^{-1} (2 fb^{-1} Run IIa) at 2.0 TeV

Key for top quark physics:
- **good lepton identification**
- **good missing E_T resolution**
- **efficient b-jet tagging capability**

Dilepton Final State

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(\ell' \nu b) \rightarrow \ell \ell' j^2 \not{E}_T$$

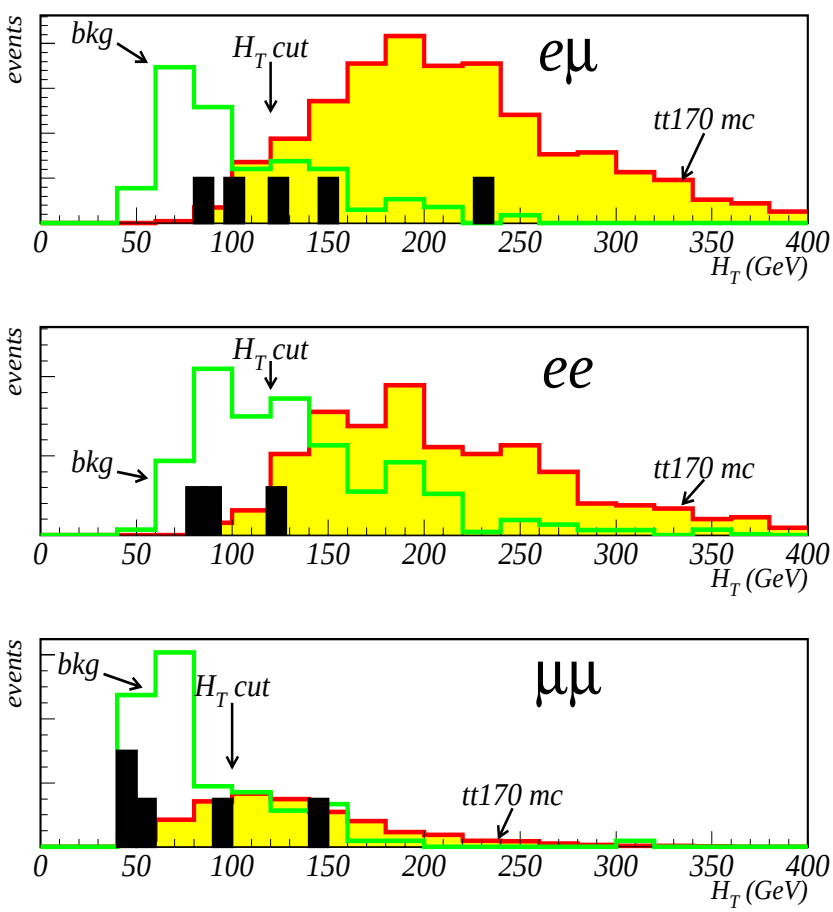
Small rate (5%) but lowest backgrounds

Characteristics:

- **two isolated high pT leptons**
- **2 jets from b-quarks**
- **significant missing transverse energy**

Major backgrounds:

- **Z($\rightarrow \ell\ell$)+jets, WW, Z$\rightarrow\tau\tau$**
- **QCD:** $b\bar{b}, c\bar{c} \rightarrow \ell\ell$
- **instrumental: misidentification**



Lepton+Jets Final State

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(q\bar{q}'b) \rightarrow \ell j^4 \not{E}_T$$

Moderate rate (15%) and reasonable backgrounds

Characteristics:

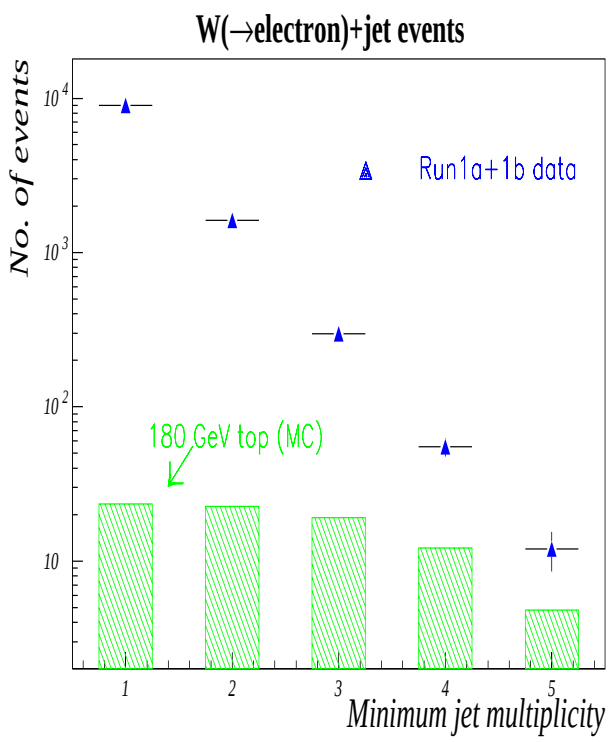
- One isolated high pT lepton
- large transverse momentum imbalance
- multiple jets

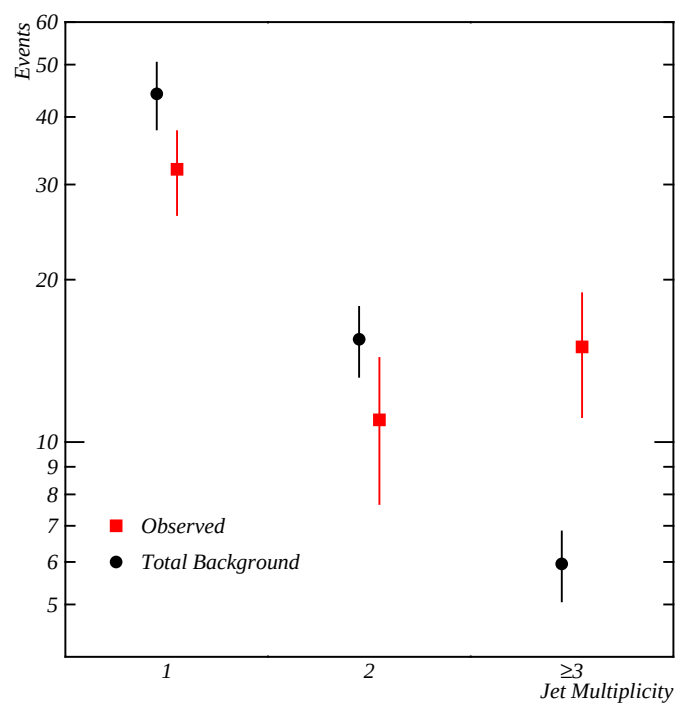
Major backgrounds:

- W+jets production
- Instrumental:
  misidentification and mismeasurement

Strategies:

- Explore the difference in topologies
- b-jets identification through (b→μ) decays





Alljets Final State

$$t\bar{t} \rightarrow (q\bar{q}'\bar{b})(q\bar{q}'b) \rightarrow j^6$$

Largest rate (44%) but highest backgrounds

Characteristics:

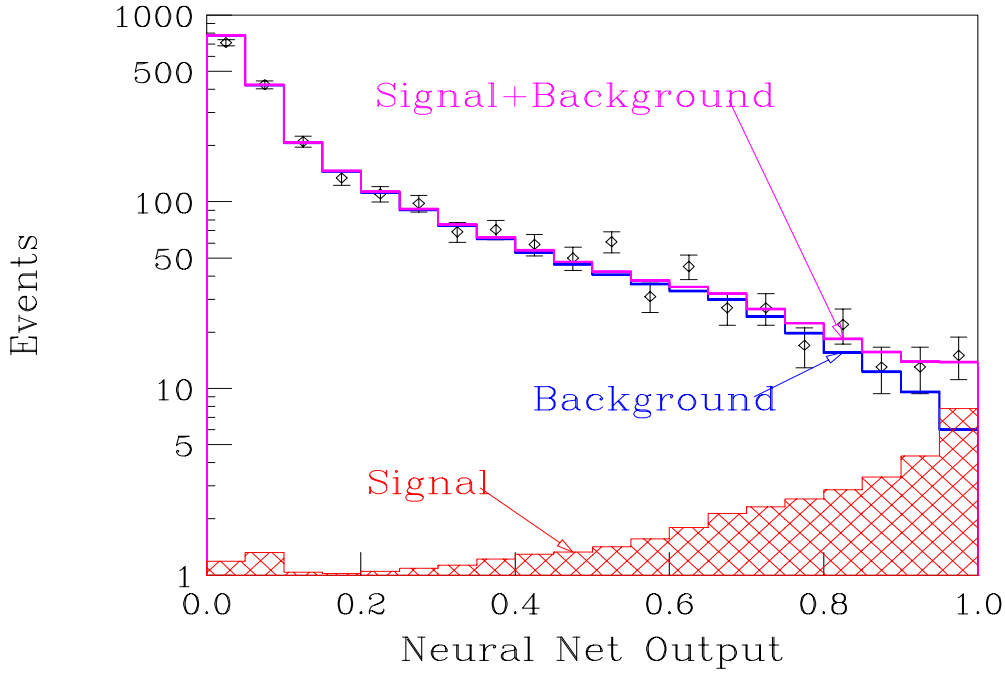
- Six or more jets (two b-jets)
- No high pT lepton nor large transverse momentum imbalance

Backgrounds:

- Huge QCD multi-jet production (S/B=1/2000 on tape)

Strategies:

- Tag b-jets using b→μ decays
- Neural network to separate signal from backgrounds



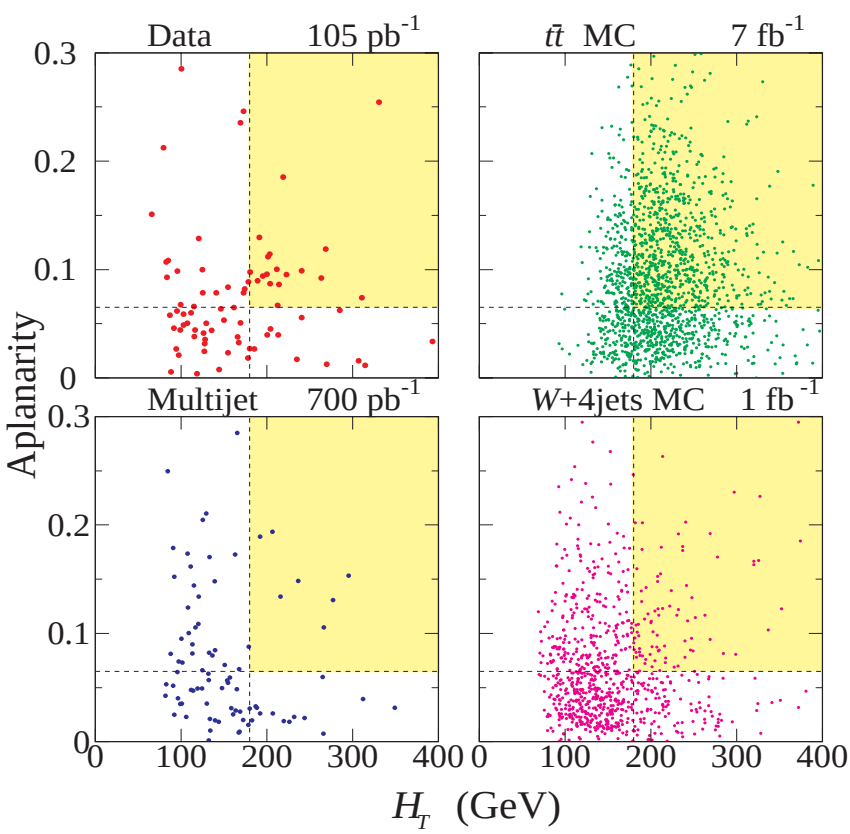
Event Selection

Top quark pair events are topologically different from most of the background events

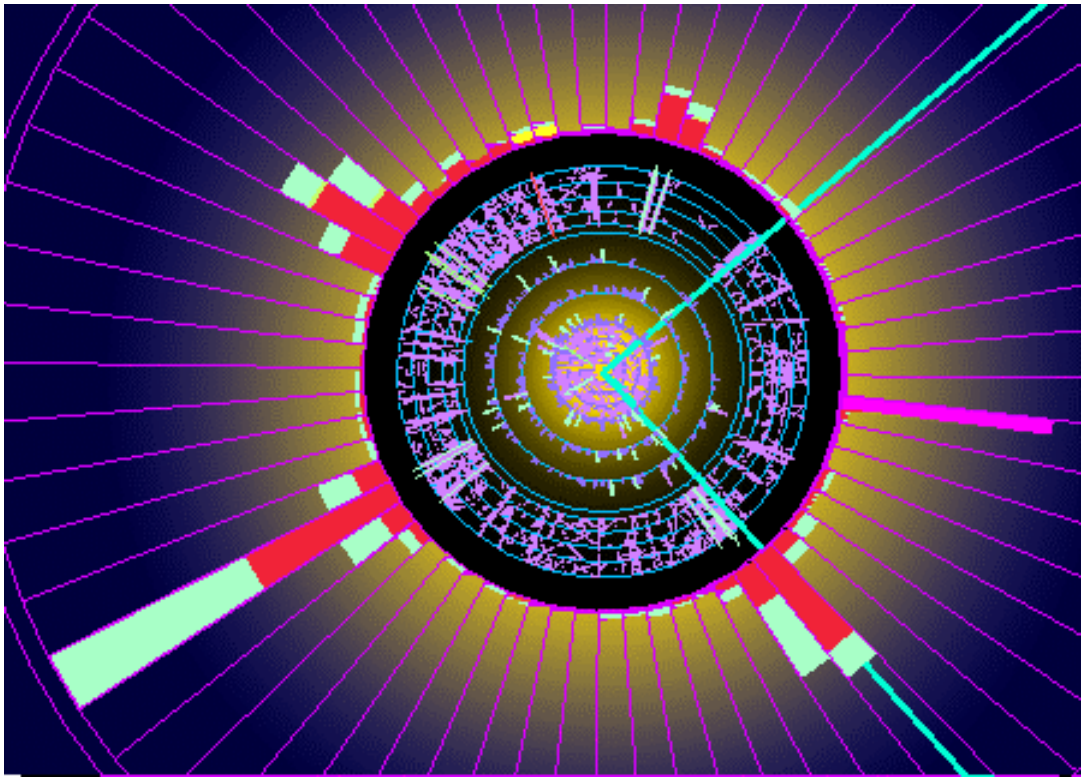
- top quark events are more spherical
- every event has two jets from b-quarks
- leptonic decays of W bosons:
  - high pT isolated leptons
  - large missing transverse momentum

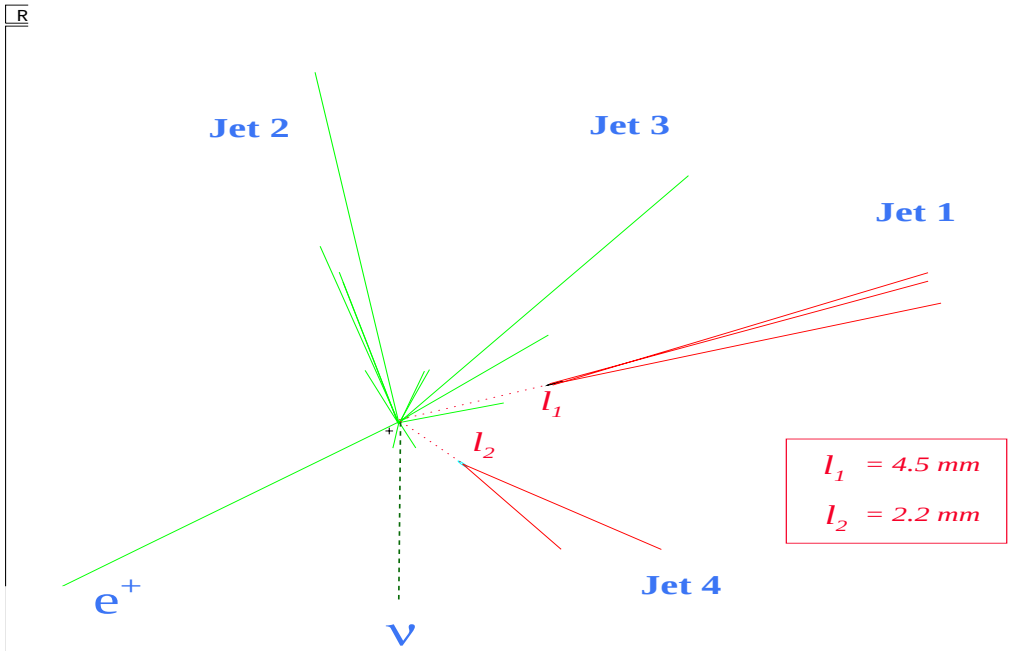
Depending on the final state, sophisticated selection criteria were developed to distinguish signal events from backgrounds

Selection of ℓ + jets events



Candidate Events





$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

24 September, 1992
run #40758, event #44414

Selection Criteria

Dilepton Final State

		eμ	ee	μμ
Lepton	E_T (GeV)	≥15	≥ 20	≥ 15
	|η|	<2.5 (e) <1.7 (μ)	<2.5	<1.7
Missing E_T (GeV)		≥20	≥ 25	–
Jets	#	≥ 2	≥ 2	≥ 2
	E_T (GeV)	≥ 20	≥ 20	≥ 20
	|η|	<2.5	<2.5	<2.5
H_T (GeV)		≥ 120 (jets+e)	≥ 120 (jets+e_1)	≥ 100 (jets)

Lepton+Jets Topological Analysis

Lepton	E_T (GeV)	>20	>20
	|η|	<2	<1.7
Missing E_T (GeV)		>25	>20
2 Jets	E_T (GeV)	>15	
	|η|	<2	
Shape	$E_T^{\ell} + \not{E}_T$	>60 GeV	
	ΣE_T^{jets}	>180 GeV	
	Aplanarity	>0.065	
Others		$\|\eta_W\|$<2	
		Veto μ-tagged events	

Selection Criteria

Lepton+Jets Tagged Analysis

- **two b-quark jets in each signal events**
- **background events have minimal heavy flavor content**
- **tag b-jet by presence of μ in jet**
  - **~20% of the signal events have a detectable μ associated with a jet**
  - **~2% of W+jets background events have a μ associated with a jet**
- **relax shape cuts to require only 3 jets**

Event Selection

		e+jets/μ	μ +jets/μ
Lepton	E_T (GeV)	>20	
	$\lvert\eta\rvert$	<2	<1.7
Missing E_T (GeV)		>20	
$Z\rightarrow\mu\mu$ fit		–	Prob(χ^2)<0.01
Soft μ		p_T>4 GeV and $\Delta R(\mu,\text{jet})<0.5$	
Jets		$\geq$ 3 jets, E_T>20 GeV, $\lvert\eta\rvert<2$	
Shape		Aplanarity>0.04	
		H_T>110 GeV	

Event Sample

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(\ell' \nu b) \rightarrow \ell \ell' j^2 \not{E}_T$$

	DØ	CDF	
	ee,e_μ,$\mu\mu$, (e_ν)	ee,e_μ,$\mu\mu$	e_τ,$\mu\tau$
data	5 (4)	9	4
background	1.4±0.4 (1.2±0.4)	2.4±0.5	2.0±0.4

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(q\bar{q}' b) \rightarrow \ell j^4 \not{E}_T$$

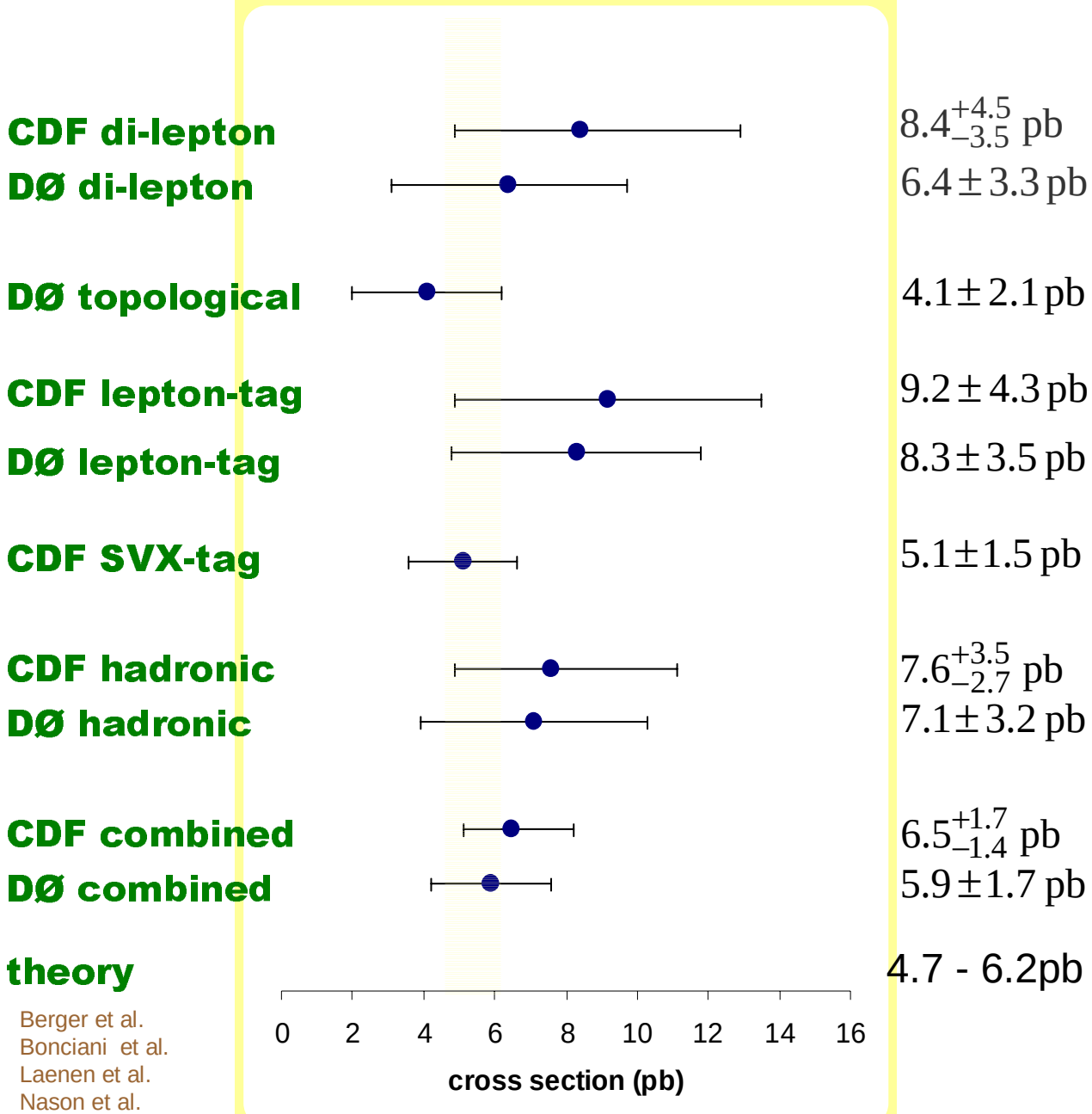
	DØ		CDF	
	topological	lepton-tag	SVX-tag	lepton-tag
data	19	11	29	25
background	8.7±1.7	2.4±0.5	8.0±1.0	13.2±1.2

11 events in common

$$t\bar{t} \rightarrow (q\bar{q}' \bar{b})(q\bar{q}' b) \rightarrow j^6$$

	DØ	CDF
data	41	187
background	24±2.4	151±10

Cross Section



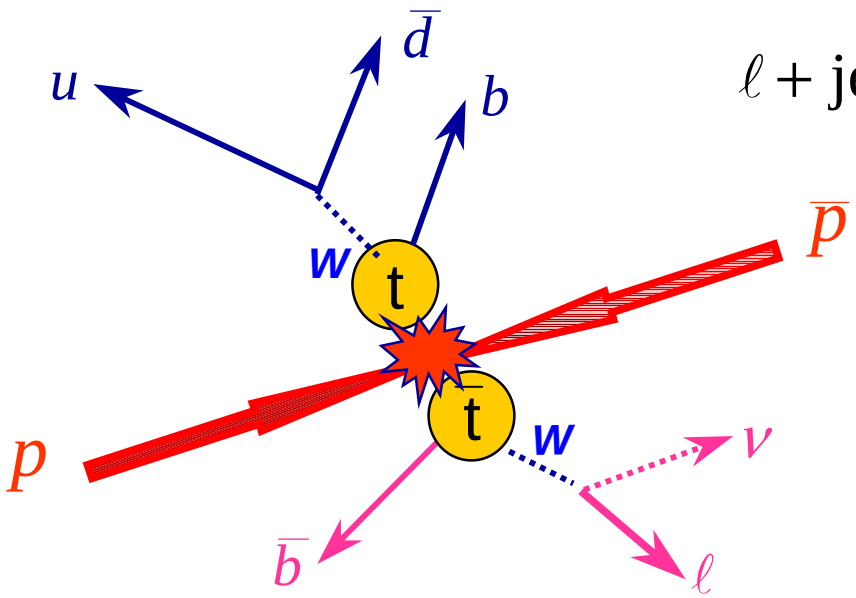
DØ: PRL 79, 1203 (1997); CDF: PRL 80, 2773 (1998) (+updates)

Theoretical uncertainty is about 10% - 20%

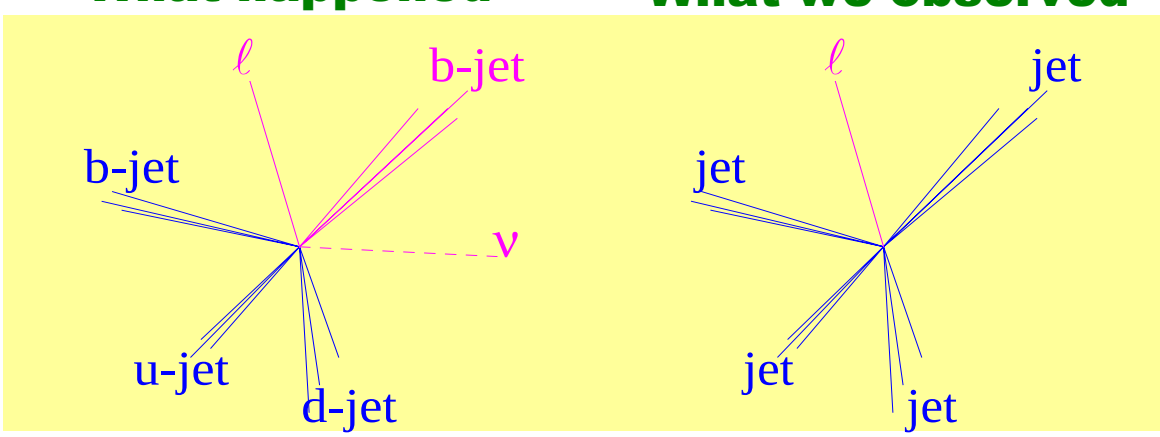
Run II precision: ~8% (stat: 4%, syst: 4%, lumi: 4%)

Lepton+Jets Mass Method

ℓ + jets $t\bar{t}$ candidates



What happened **What we observed**



For a signal event, we have one unknown (p_z^ν) and three constraints

$$m(\ell\nu) = m(jj) = M_W$$
$$m(j\ell\nu) = m(jjj)$$

Top quark mass can be determined through a 2-constraint fit to event kinematics

Lepton+Jets Mass Method

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(q\bar{q}'b) \rightarrow \ell j^4 \not{E}_T$$

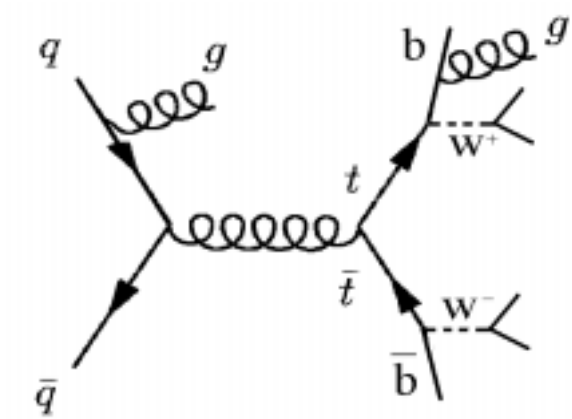
Jet assignment ambiguity

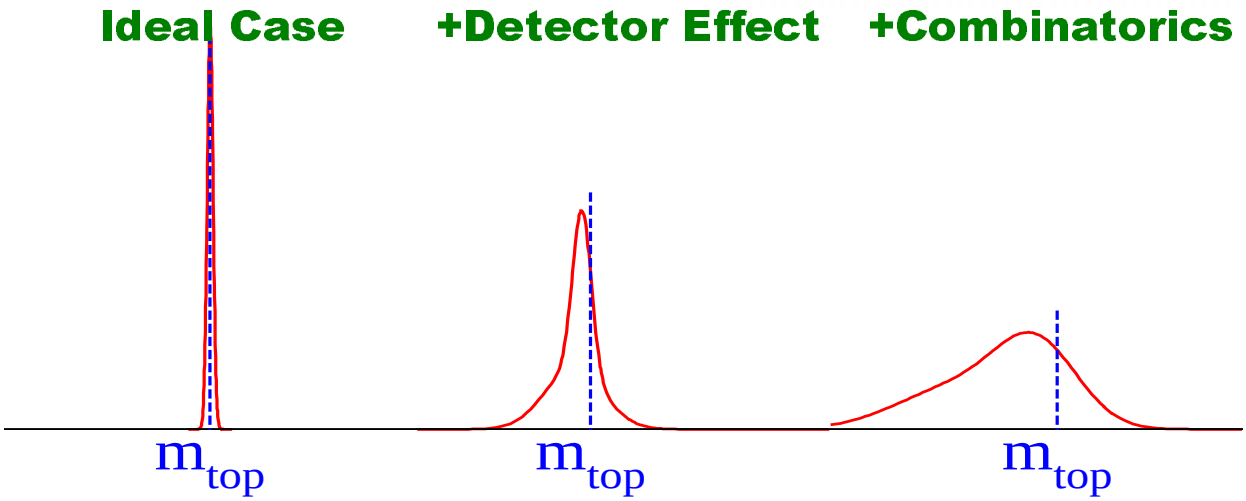
- 12 if no jets is b-tagged
- 6 if one of the jets is b-tagged
- 2 if two jets are b-tagged

Additional complications from

- background events
- detector effect (mismeasurement + resolution)
- initial and final state radiations

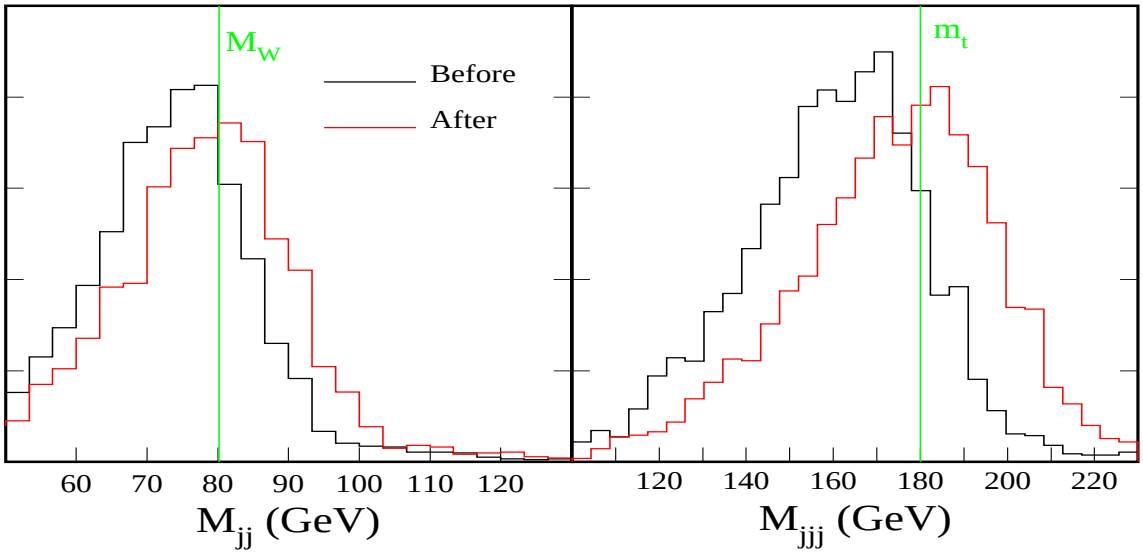
Compare to Monte Carlo to measure the top quark mass



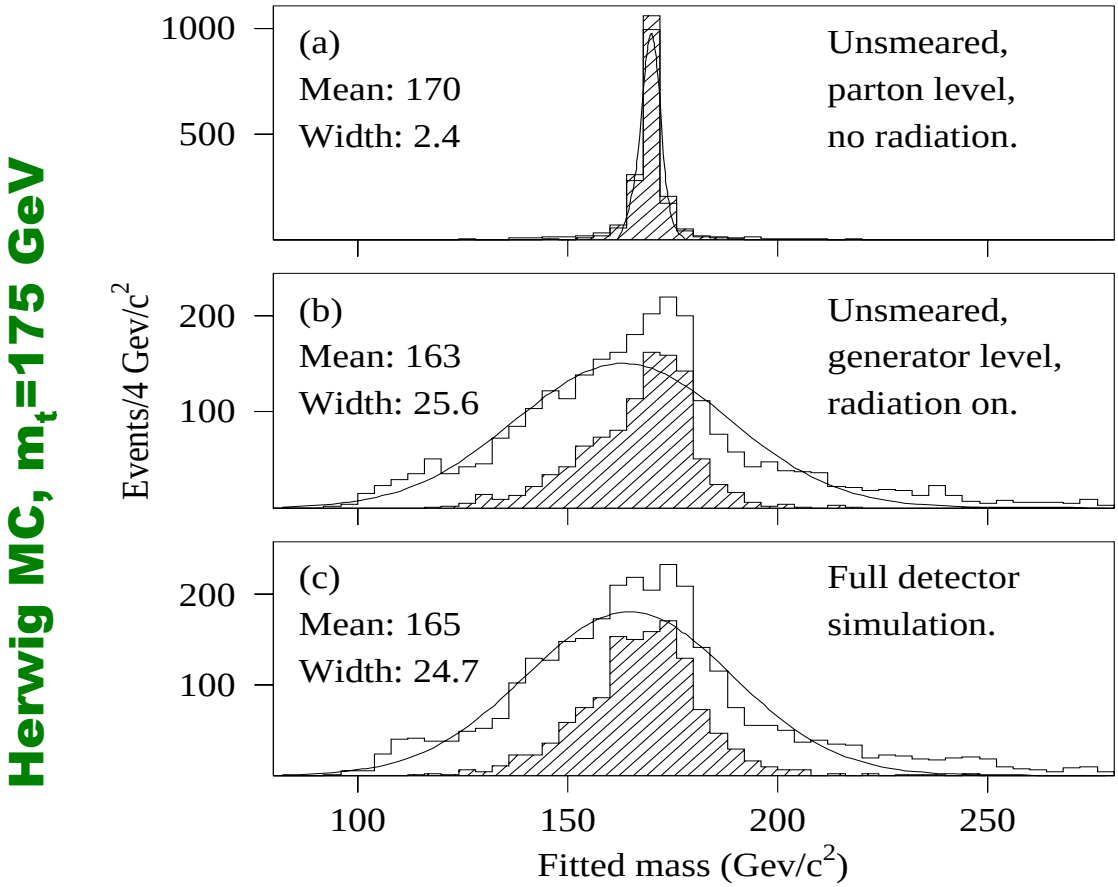


Lepton+Jets Mass Method

Jet Energy Scale



Resolutions and Combinatorics



Lepton+Jets Mass Method

The measured distribution $f(x)$ is compared to those from signal $g_s(x,m_t)$ and from background $g_b(x)$ to extract the top quark mass using a likelihood method

$$L(n_s,n_b,m_t) = \frac{e^{-(n_s+n_b)}}{N!}(n_s+n_b)^N \times \frac{1}{\sqrt{2\pi}\sigma_b} e^{-\frac{(n_b-\langle n_b\rangle)^2}{2\sigma_b^2}} \times \prod_{i=1}^{N} \frac{n_s g_s(x_i,m_t)+n_b g_b(x_i)}{n_s+n_b}$$

Poisson statistics

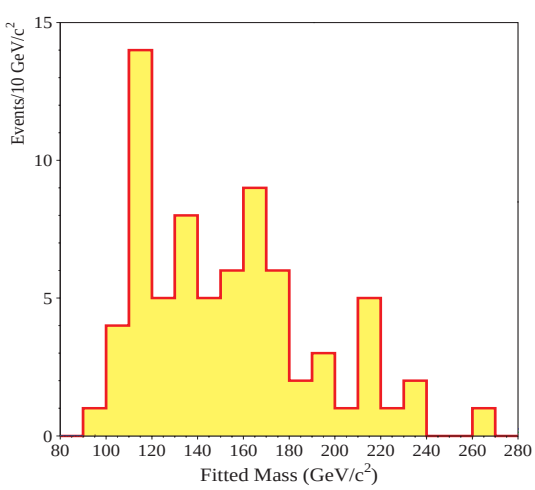
Background constraint

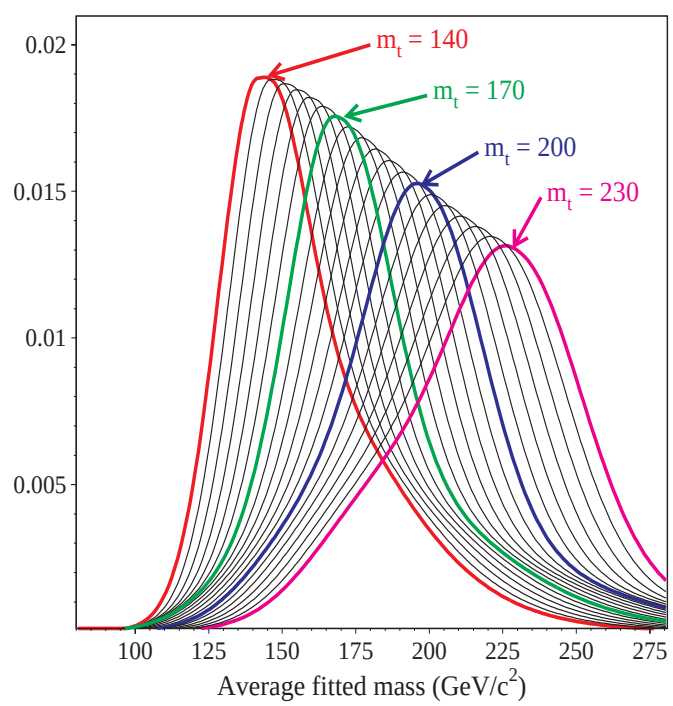
Probability density distribution for the measured variable

$n_s =$ **# of signal events**

$n_b =$ **# of background events**

$m_t =$ **top quark mass**





Multivariate Discriminants

- **Some of the cross section selection are mass biased and need to be replaced**

- **DØ used four-variable multivariate discriminants**

$$x_1 = \not{E}_T \text{ (transverse momentum imbalance)}$$
$$x_2 = A \text{ (Aplanarity)}$$
$$x_3 = \frac{\Sigma_{i=2}^{N} E_T^j}{\Sigma_{i=1}^{N} E_L^j} \text{ (centrality)}$$
$$x_4 = \frac{(\Delta R_{jj}^{\min}) E_T^{\min}}{E_T^L} \text{ (clusterness)}$$

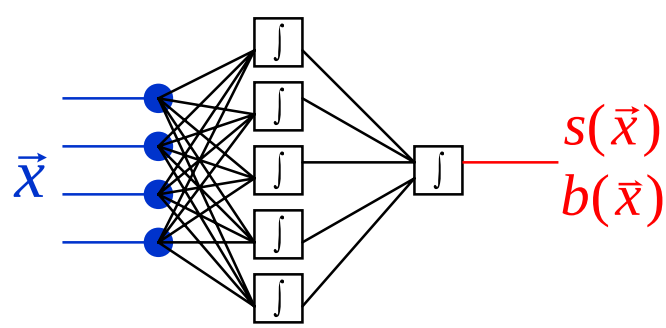
Likelihood:

$$L_i(\vec{x}) = \frac{s_i(\vec{x})}{b_i(\vec{x})} \text{ for each event}$$

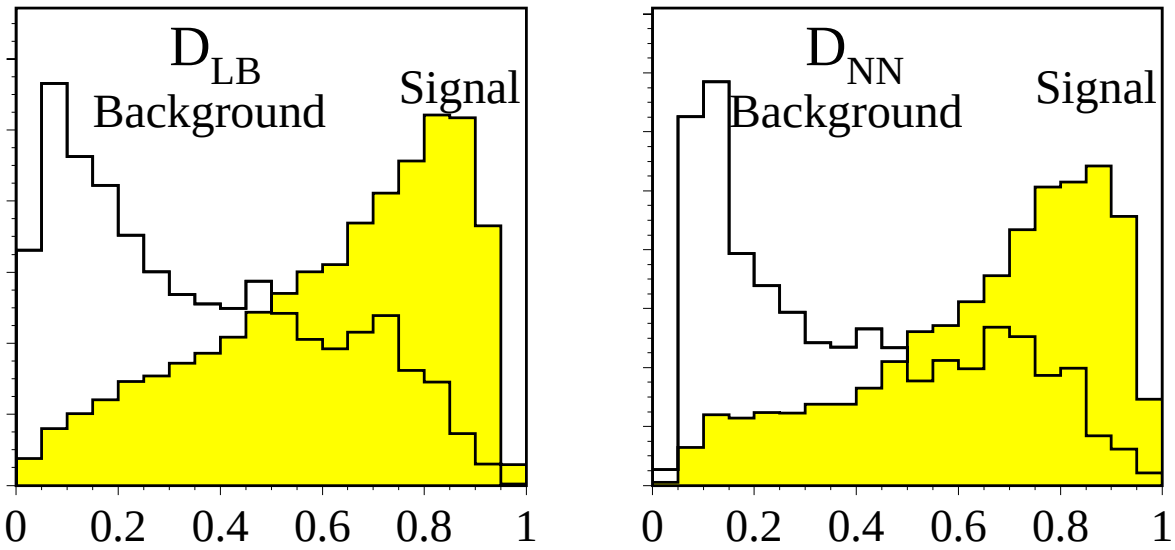
$$D_{LB} = \frac{\prod_{i=1}^{N} L_i(\vec{x})}{1 + \prod_{i=1}^{N} L_i(\vec{x})} \Rightarrow \{0-1\}$$

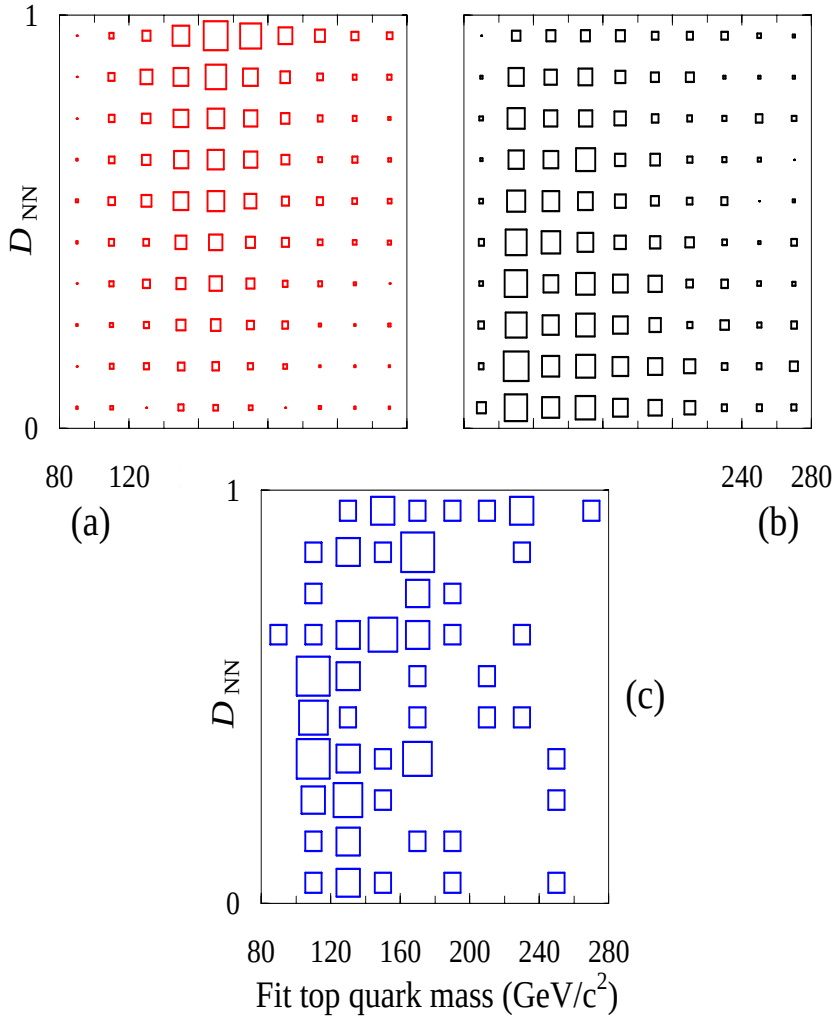
Neural Network:

$$D_{NN} = \frac{s(\vec{x})}{s(\vec{x}) + b(\vec{x})}$$
$$\Rightarrow \{0-1\}$$



Multivariate Discriminants





Lepton+Jets Mass Analysis

Analysis Details

$E_T^{\ell} > 20$ GeV $\quad |\eta_e| < 2.0 \quad |\eta_\mu| < 1.7$

$\not{E}_T > 20$ GeV

$\not{E}_T^{cal} > 25$ GeV for e + jets; $\not{E}_T^{cal} > 20$ GeV for μ + jets

≥ 4 jets, $E_T > 15$ GeV, $|\eta_{\text{jet}}| < 2.0$

For events with $b \to \mu$ tagging

$p_T^{\mu} > 4$ GeV and $\Delta R = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} < 0.5$ of a jet

For events without $b \to \mu$ tagging

$E_T^L \equiv (E_T^{\ell} + \not{E}_T) > 60$ GeV and $|\eta_W| < 2.0$

91 events selected (7 events have $b \to \mu$ tagged)

Perform kinematic fit on this sample

require $\chi^2 < 10$ and select fit with smallest χ^2

$\Rightarrow$ 77 events fitted successfully (5 $b \to \mu$ tagged events)

Mass from Lepton+Jets

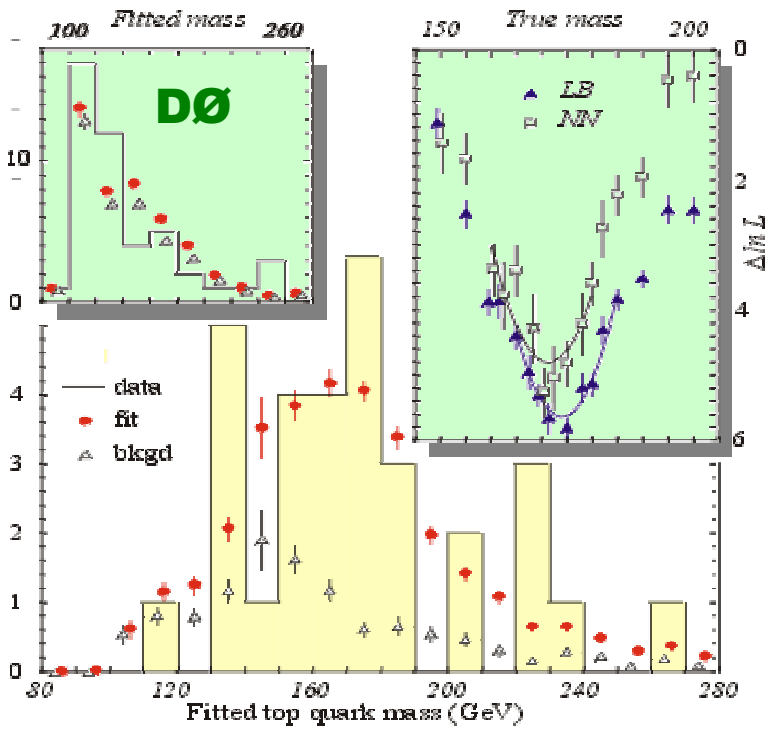
$t\bar{t} \rightarrow (\ell \nu \bar{b})(q\bar{q}'b)$

173.3±5.6±5.5 GeV

Largest systematics

Jet energy	**4.0 GeV**
Monte Carlo	**3.1 GeV**
Noise/pile-up	**1.3 GeV**

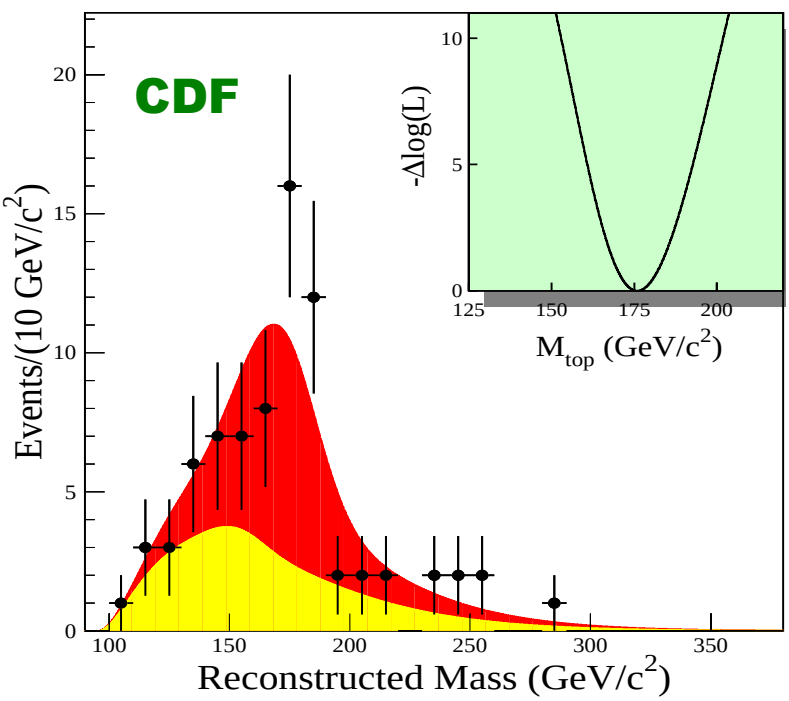
PRL 79, 1197 (1997)
PRD 58, 052001 (1998)



176.1±5.1±5.3 GeV

Largest systematics

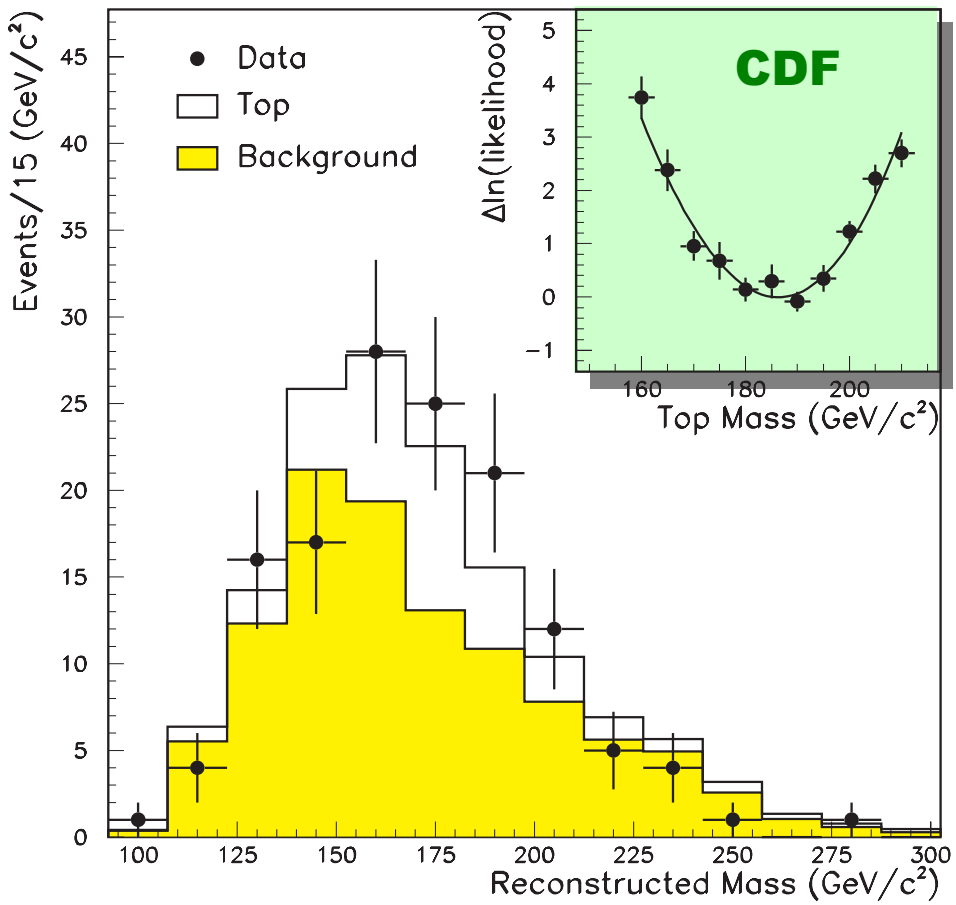
Jet energy	**4.4 GeV**
Monte Carlo	**2.6 GeV**
Background	**1.3 GeV**



Mass from Alljets

$$t\bar{t} \rightarrow (q\bar{q}'b)(q\bar{q}'\bar{b}) \rightarrow j^6$$

m_t can also determined from alljets final state from a 3-constraint fit



m_t = 186.0±10.0±5.7 GeV

Largest systematics

Jet scale	4.4 GeV
Monte Carlo	1.8 GeV
Background	1.3 GeV

Dilepton Mass Method

$$t\bar{t} \rightarrow (\ell\nu b)(\ell'\nu b) \rightarrow \ell\ell' j^2 \not{E}_T$$

The final state is underconstrained

- **among the 6 neutrino momentum components, only Σp_T^{ν} are measured $\Rightarrow$ four unknowns**

- **three constraints:**

$$m(\ell\nu) = m(\ell'\nu) = M_W$$
$$m(\ell\nu b) = m(\ell'\nu b)$$

Nevertheless, the final state momentum and angular information is sensitive to the top quark mass.

- **assuming a m_t, calculate a weight for every event characterizing how likely that the event is consistent with the assumed m_t**

- **sum the weight over candidate events**

- **repeat the process for different values of m_t, $\Rightarrow$ weight function $W(m_t)$**

- **the top quark mass is extracted by fitting the observed $W(m_t)$ distribution to those from MC**

K. Kondo, J. Phys. Soc. Jpn. 57, 4126 (1988) and 60, 836 (1991)
R.H. Dalitz and G.R. Goldstein, PRD 51, 4763 (1995).

Dilepton Mass Method

$$t\bar{t} \rightarrow (\ell \nu b)(\ell' \nu b) \rightarrow \ell \ell' j^2 \not{E}_T$$

Matrix element and neutrino weightings

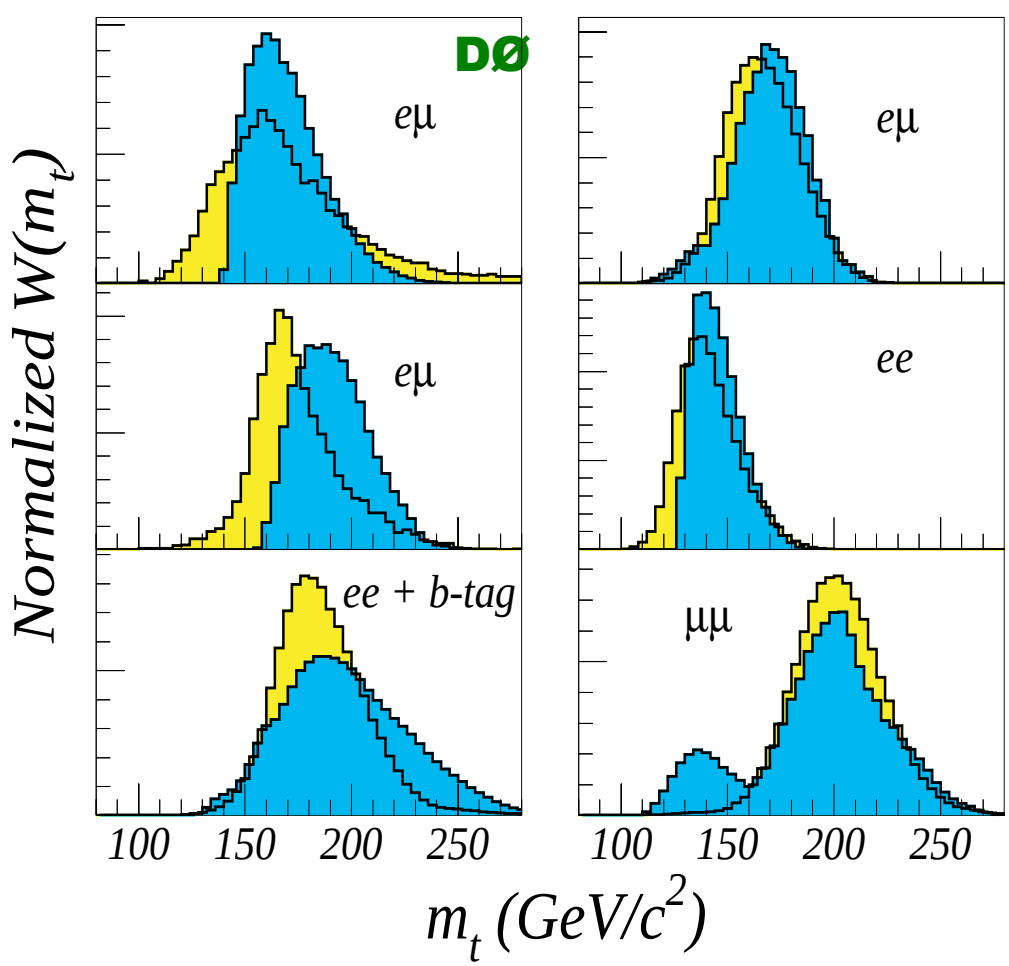
$$w_i^M(m_t) \sim f(x) f(\bar{x}) p(E_i^{\ell^+}|m_t) p(E_i^{\ell^-}|m_t)$$

$$w_i^\nu(m_t) \sim \iint d\eta d\bar{\eta} g(\eta|m_t) g(\bar{\eta}|m_t) \exp[-\frac{(\vec{p}_T - \vec{p}_T^{\,\nu} - \vec{p}_T^{\,\bar{\nu}})^2}{2\sigma^2}]$$

$f(x)$: parton distribution function

$p(E^\ell|m_t)$: lepton energy probability for a given m_t

$g(\eta|m_t)$: lepton η probability for a given m_t



Mass from Dilepton

$$t\bar{t} \rightarrow (\ell \nu \bar{b})(\ell' \nu b)$$

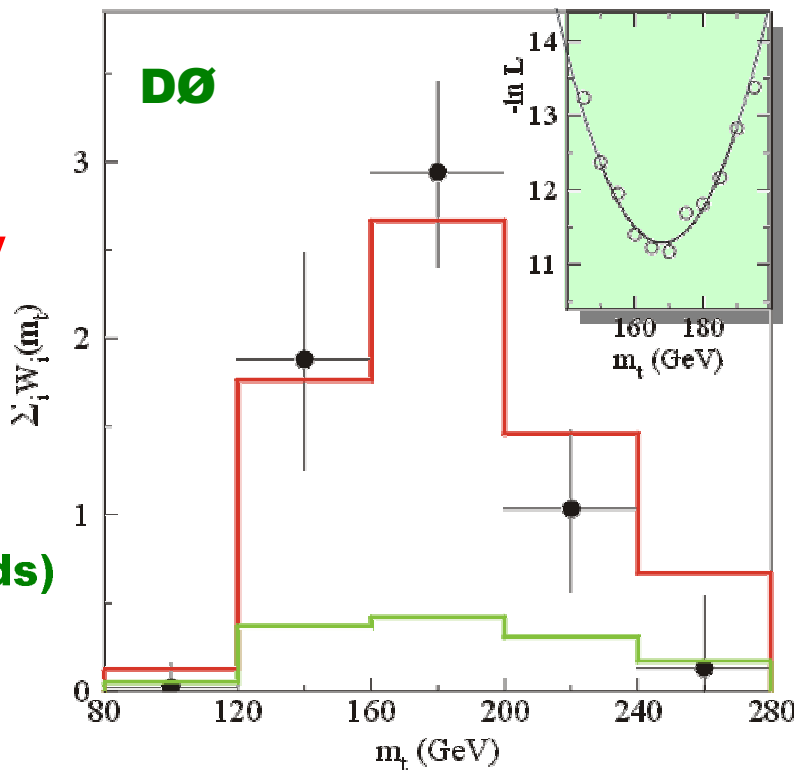
168.4±12.3±3.6 GeV

Largest systematics

Jet energy	**2.4 GeV**
Monte Carlo	**1.8 GeV**
Noise/pile-up	**1.3 GeV**

(combining both methods)

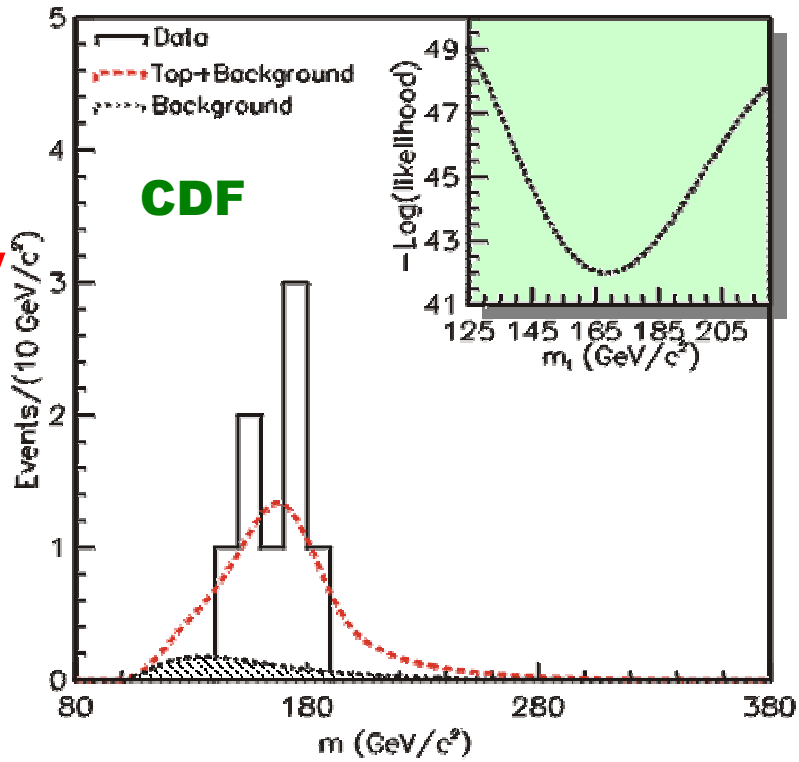
PRL 80, 2063 (1998)
PRD 60, 05001 (1999)



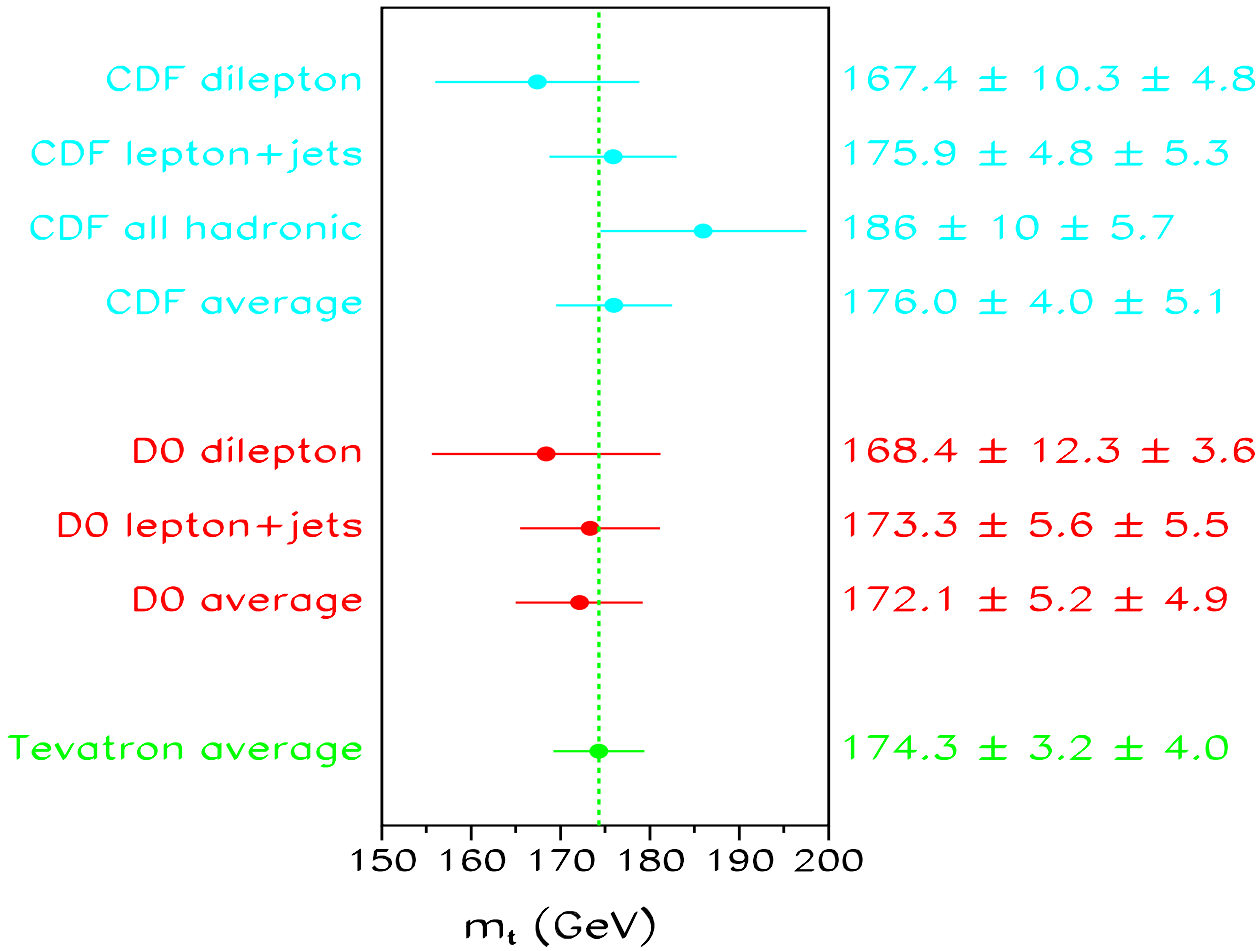
167.4±10.3±4.8 GeV

Largest systematics

Jet energy	**3.8 GeV**
Gluon radiation	**2.7 GeV**

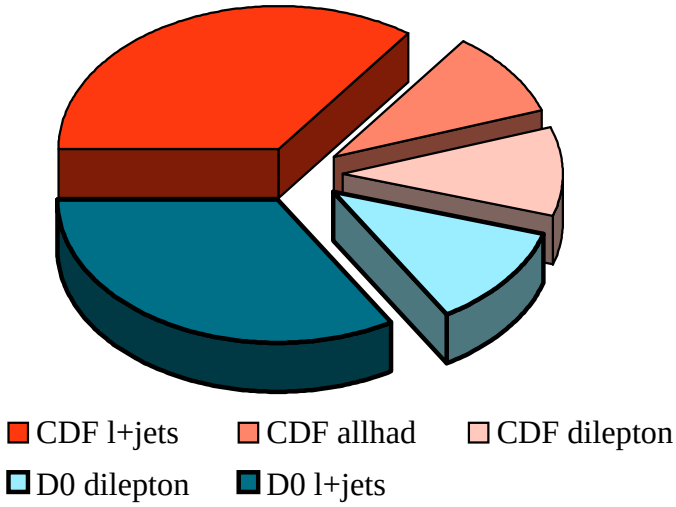


Top Quark Mass Summary



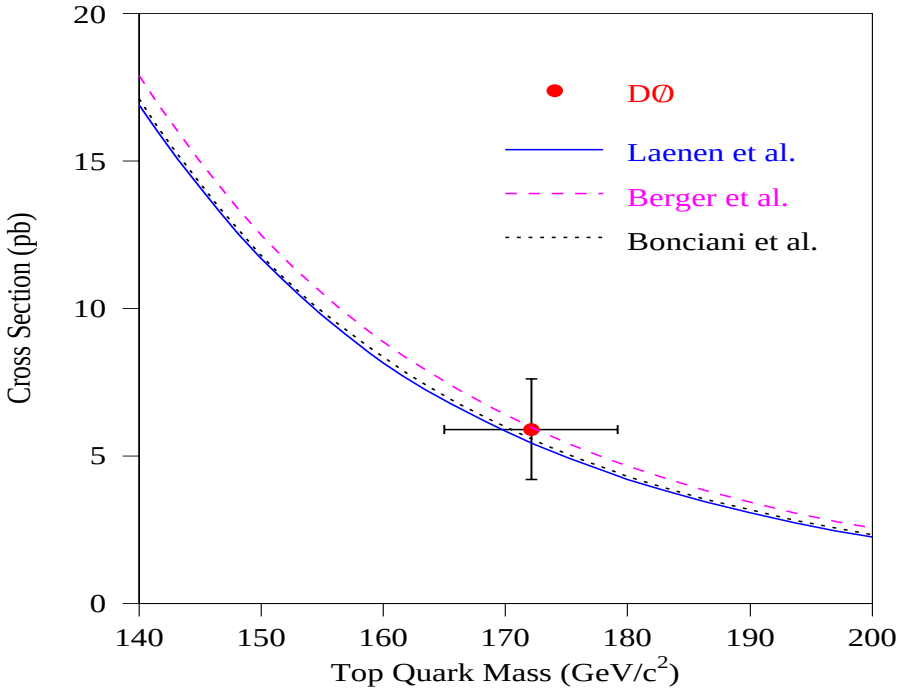
$$m_t = 174.3 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})\ \text{GeV}$$
$$= 174.3 \pm 5.1\ \text{GeV}$$

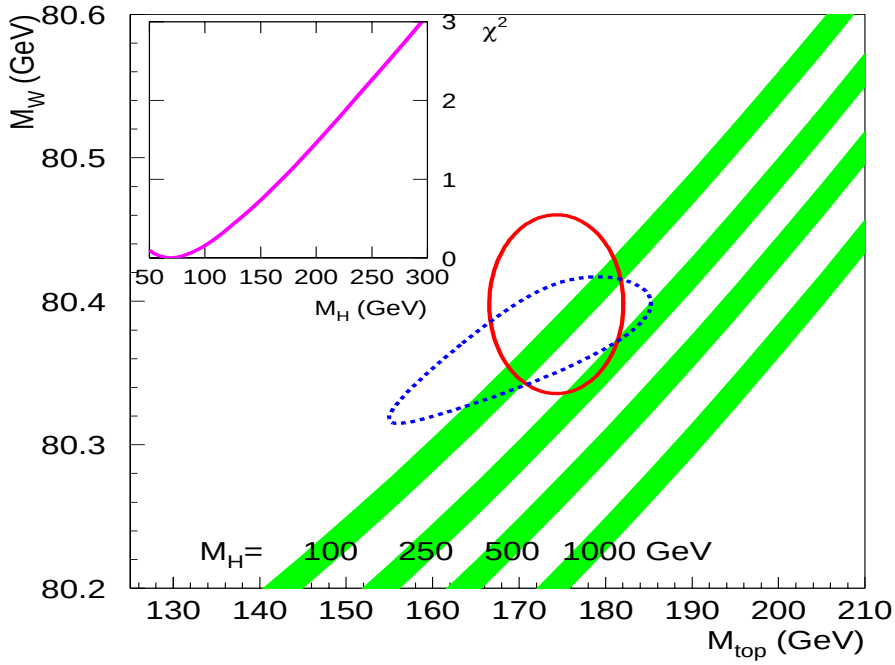
Relative weight in top mass average



Standard Model Comparison

- **Good agreement between observation and theoretical calculations**
- **Data prefer a low Higgs mass**

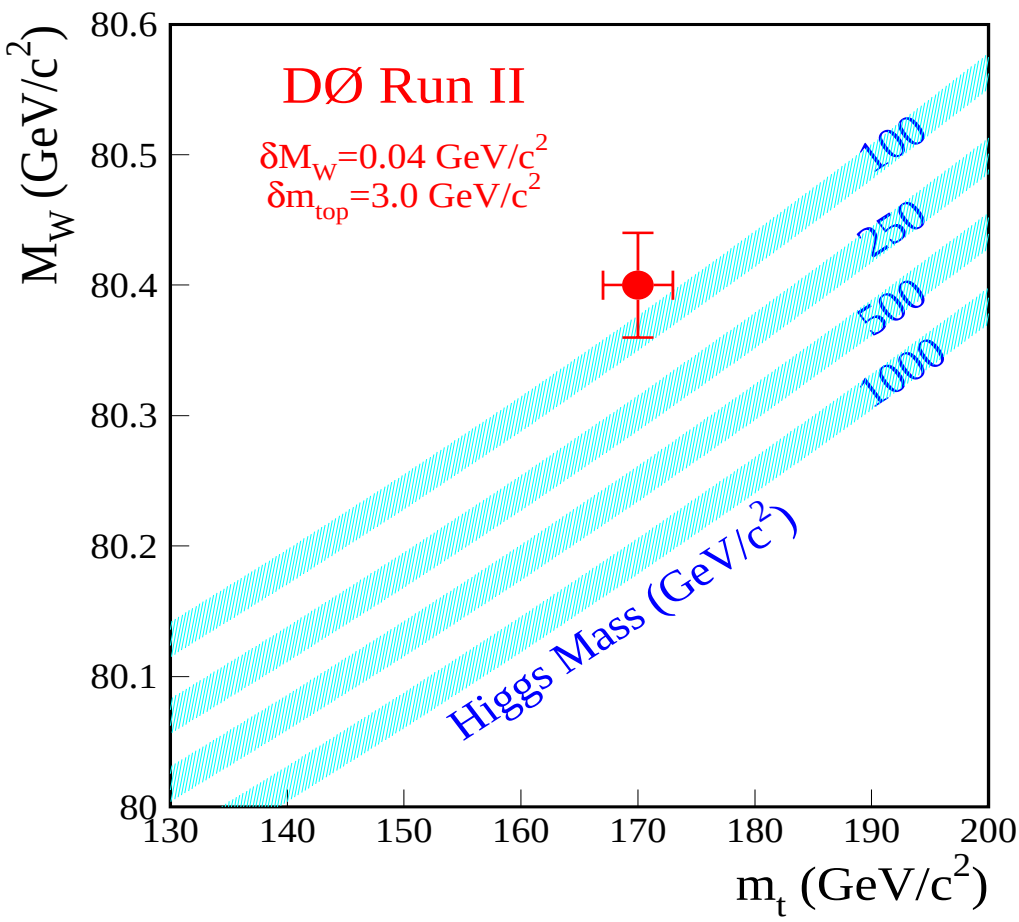




Run II Mass Measurement

Statistical and systematic errors contribute equally to the total errors of the present measurements

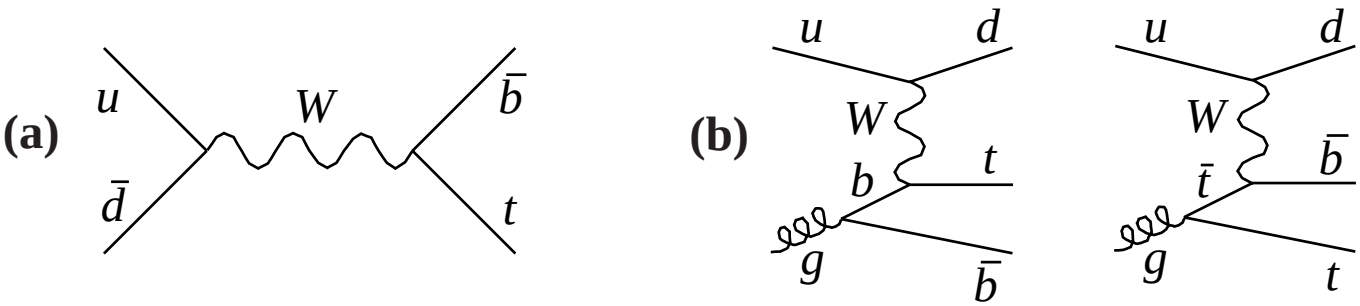
Most of the errors are expected to scale with $1/\sqrt{N}$, the δm_t is expected to reduce to 3 GeV or less



Combined with the data from LEP/SLC, the Higgs mass can be constrained to be within 30%

Single Top Production

Single top quark is produced through electroweak processes



In the standard model

$$\sigma(p\bar{p} \to tb + X) \propto \Gamma(t \to Wb) \propto |V_{tb}|^2$$

$$\sigma(W^* \to tb) = 0.72 \pm 0.10 \text{ pb}$$

$$\sigma(Wg \to tbq) = 1.7 \pm 0.2 \text{ pb}$$

Measure single top quark cross section

- **Direct access to the Wtb vertex**
- **Directly measure the top quark decay width and CKM matrix element**
- **Probe anomalous couplings**

Final State $W^* \to tb \to Wb\bar{b} \to (\ell\nu)b\bar{b}$

$Wg \to tbq \to Wb\bar{b}q \to (\ell\nu)b\bar{b}q$

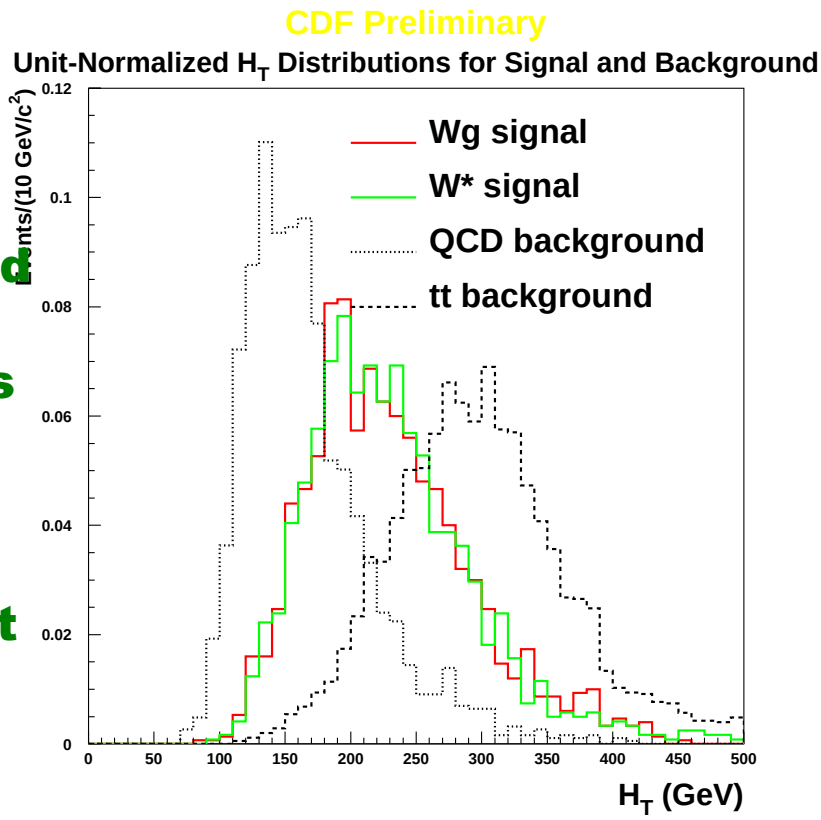
(In Wg mode, one of the b-jets is very soft)

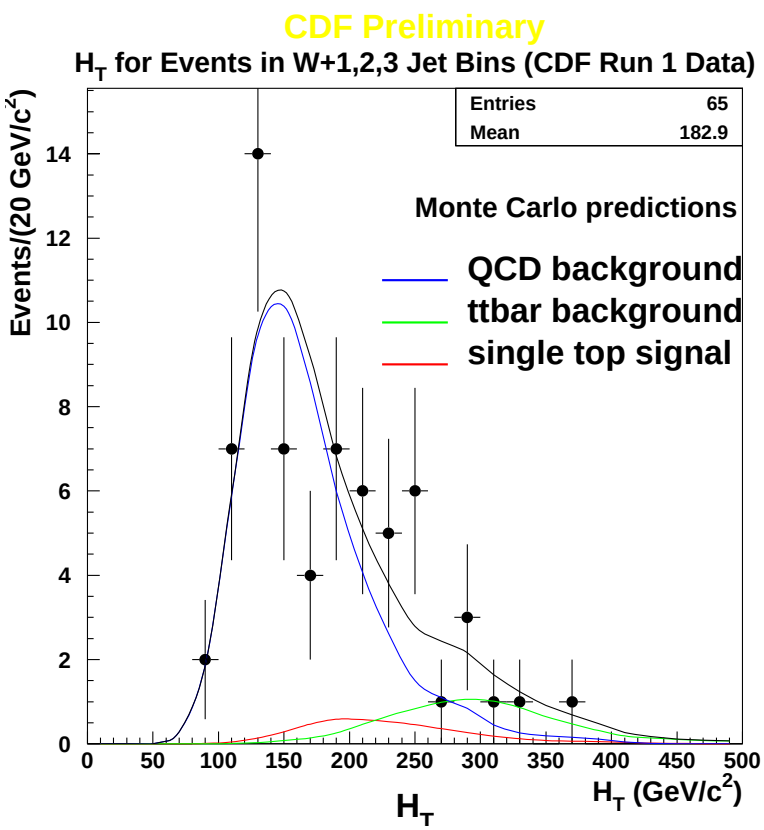
Major backgrounds: $t\bar{t}$ **and** $Wb\bar{b}$ **production**

Single Top Production

In many kinematic distributions, the signal is sandwiched between two major background sources

Neither experiment were able to extract a signal in Run I





CDF:

$\sigma < 13.5$ pb @ 95% CL

DØ:

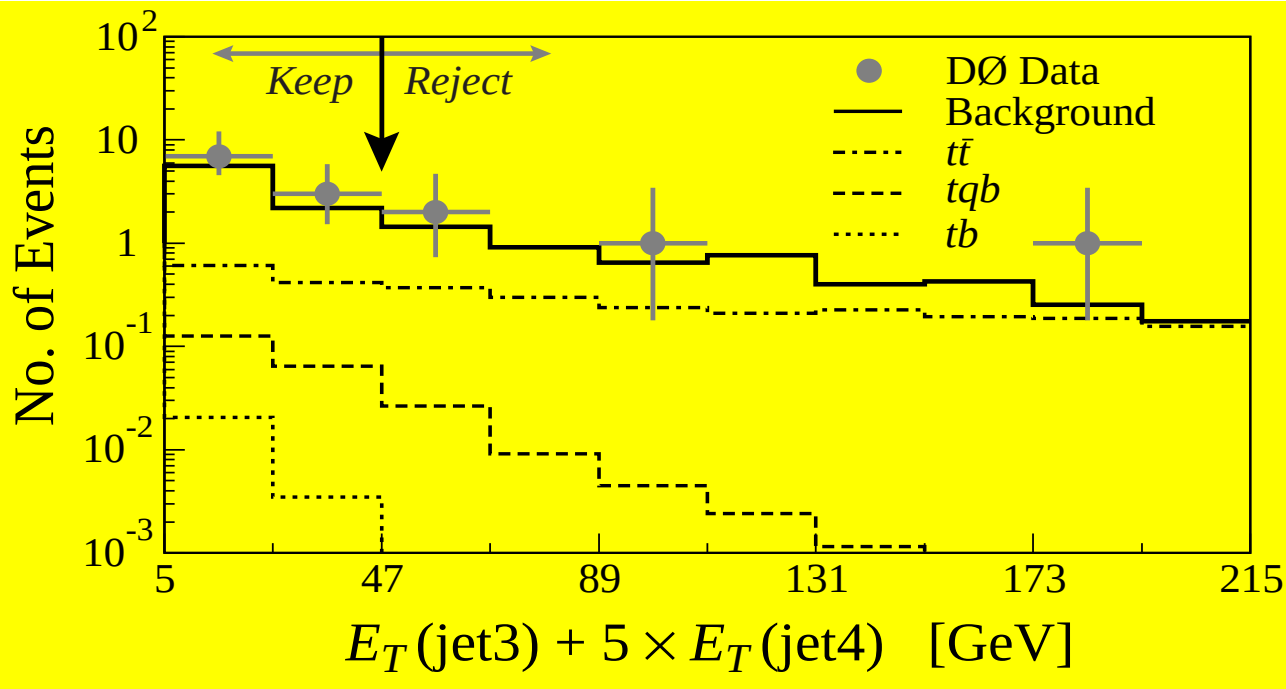
$W^* \to tb$: $\sigma < 39$ pb

$Wg \to tbq$: $\sigma < 58$ pb

Single Top Production

Single top search suffers from

- **small production cross section**
- **in Wg production, one of the two b-jets is soft and mostly in the forward region**
- **jet multiplicity is low**
- **inefficient b-jet tagging**



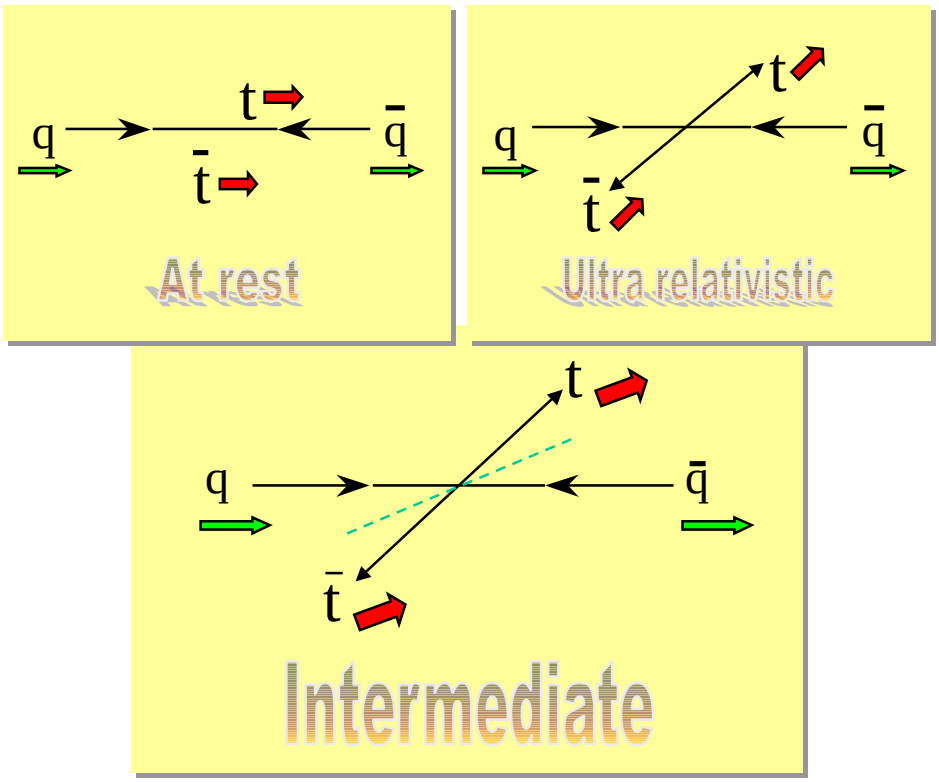
In Run IIa

- **a factor of 20 increase in luminosity**
- **expect to have a factor of 2.5 more from the improved detector and tools**

We expect to observe this process in Run II and measure $\delta\Gamma_t \sim 20\%\Gamma_t$

Spin Correlation

The spins of t and $\bar{t}$ produced from $q\bar{q}$ annihilation are expected to have strong correlations



1) Since $\Gamma_t = \Gamma(t \to Wb) \approx 1.5\ GeV\ >>\ \Lambda_{QCD} \approx 150\ MeV$ top quarks decay before hadronization

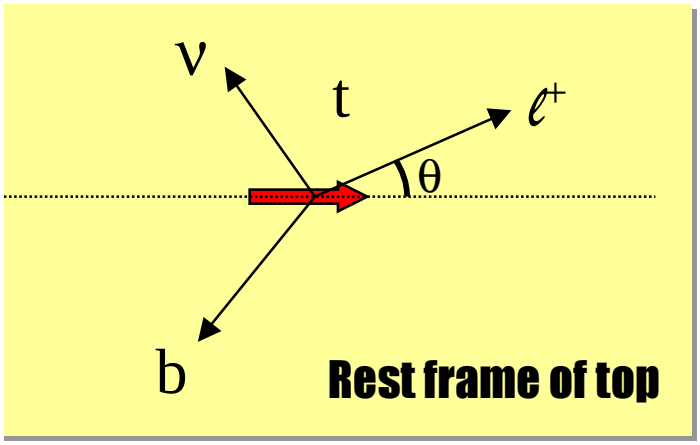
2) the polarization of the top quark is carried by its decay products

3) At $\sqrt{s} = 1.8$ TeV, 90% of $t\bar{t}$ is produced through $q\bar{q}$ annihilation

The top quark polarization can be reconstructed, not possible for other quarks!

Spin Correlation

Charged leptons and down-type quarks are most sensitive to the top quark polarization



$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_i)} = \frac{1+\alpha_i\cos\theta_i}{2}$$

Particle$_i$	α_i
l^+ or d	1
ν or u	-0.31
W^+	0.41
b	-0.41

- **Down-type quarks are impractical to identify, only dilepton events are considered**
- **In an optimized spin quantization basis, only like-spin combinations are produced**
  (G. Mahlon and S. Parke, PLB 411, 173 (1997))
- **In this basis, the spin correlation can be expressed using angles**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

correlation parameter
SM value ≈ 0.9

Spin Correlation

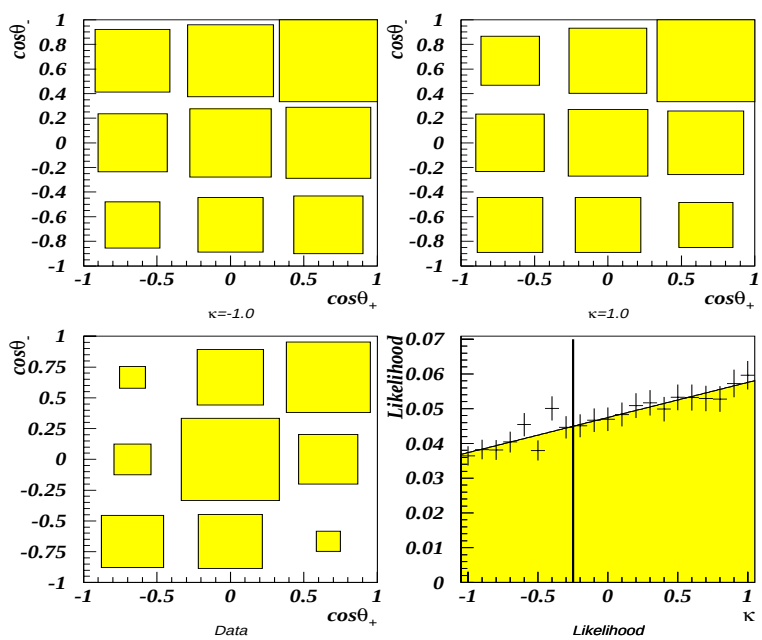
- direct probes the properties of 'bare' quarks, free of hadronization effect

- probes for non-standard interactions at the production as well as at the decay vertices

Six dilepton events are analyzed assuming $t\bar{t}$ decay hypothesis and $m_t = 175\ GeV$

Both lepton and jet pairings and multiple Neutrino solutions are considered and weighted

The sensitivity is limited by statistics!



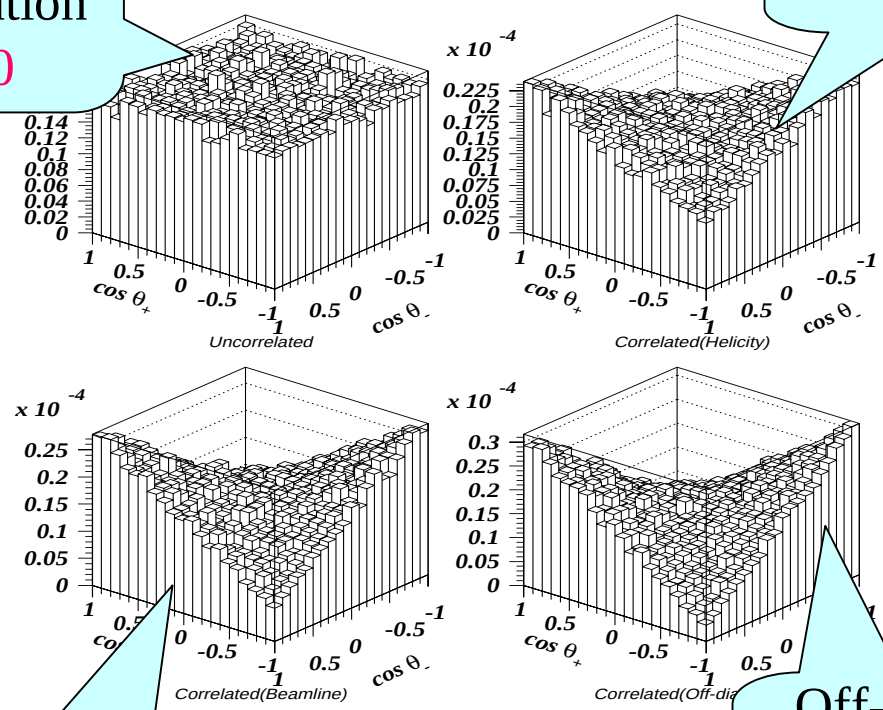
$\kappa > -0.25$ @ 68% CL

DØ: PRL 85, 256 (2000)

Spin Correlation

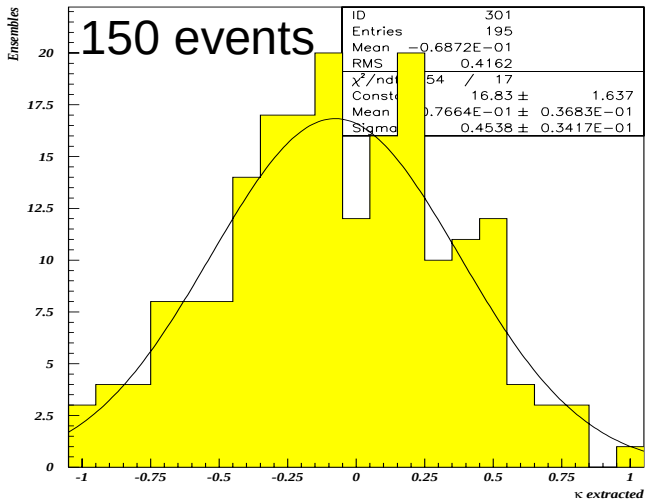
No spin correlation
κ=0

Helicity basis
κ=0.40



Beamline basis
κ=0.68

Off-diagonal basis
κ=0.87



κ

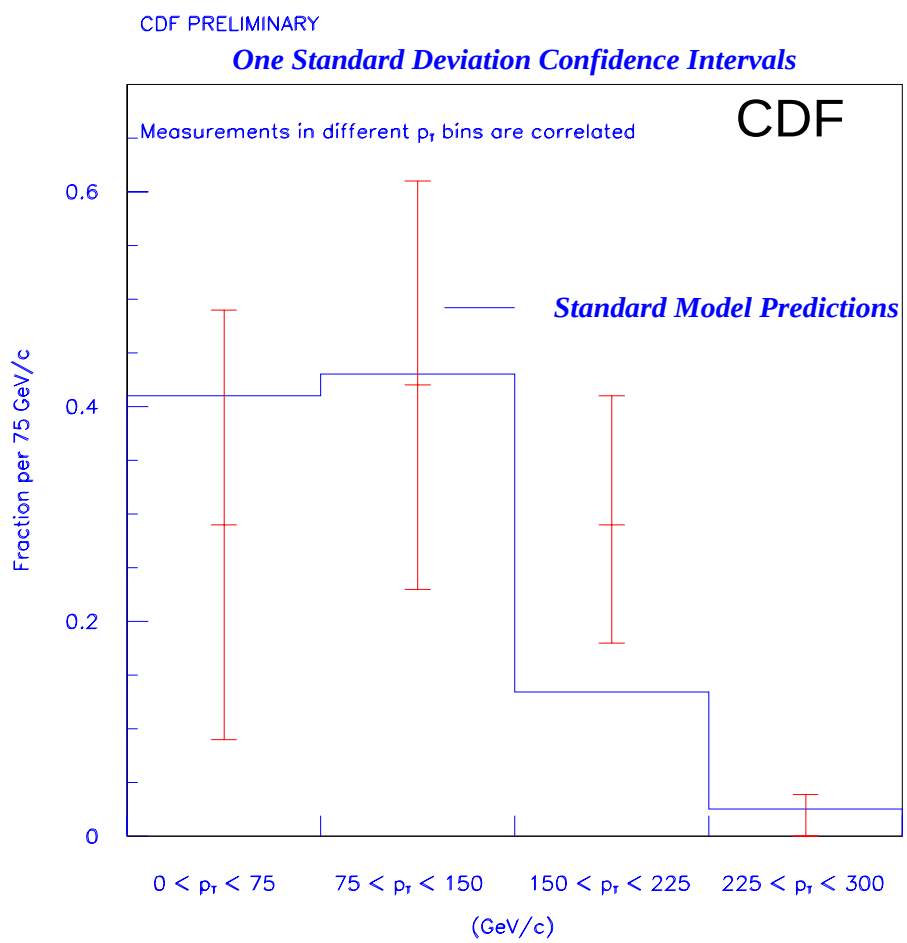
More than 150 dilepton events expected are expected from Run IIa

κ=0 and κ=1 can be separated at more than 2σ level

Transverse Momentum

Top Quark Differential Cross Section

$$R_1 + R_2 = 0.72^{+0.13}_{-0.13}(\text{stat})^{+0.06}_{-0.06}(\text{syst})$$
$$R_4 < 0.114 \text{ at } 95\% \text{ C.L.}$$



p_T Bin	Measured Fraction of Top Quarks
$0 < p_T < 75$ GeV/c	$R_1 = 0.29^{+0.18}_{-0.18}(\text{stat})^{+0.08}_{-0.08}(\text{syst})$
$75 < p_T < 150$ GeV/c	$R_2 = 0.42^{+0.18}_{-0.18}(\text{stat})^{+0.05}_{-0.07}(\text{syst})$
$150 < p_T < 225$ GeV/c	$R_3 = 0.29^{+0.12}_{-0.10}(\text{stat})^{+0.06}_{-0.05}(\text{syst})$
$225 < p_T < 300$ GeV/c	$R_4 = 0.000^{+0.035}_{-0.000}(\text{stat})^{+0.019}_{-0.000}(\text{syst})$

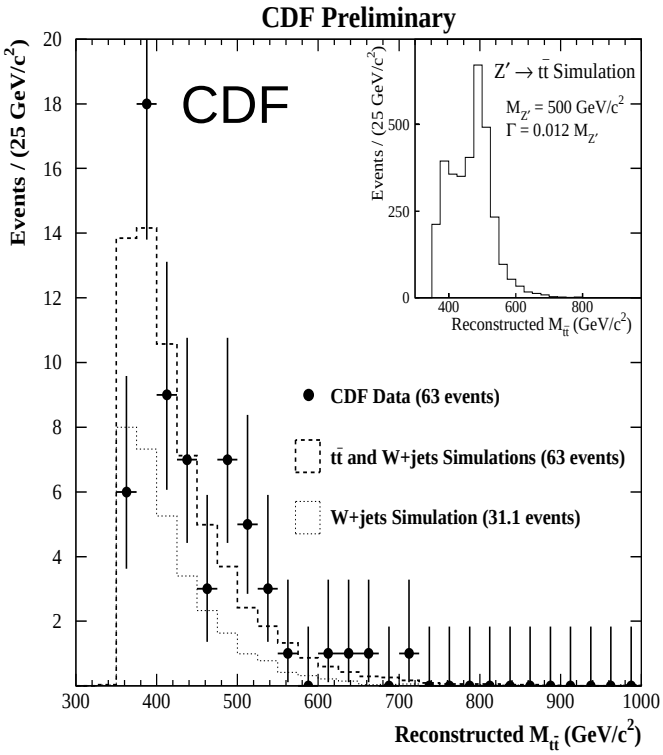
Another tool for investigating anomalous tt production mechanisms

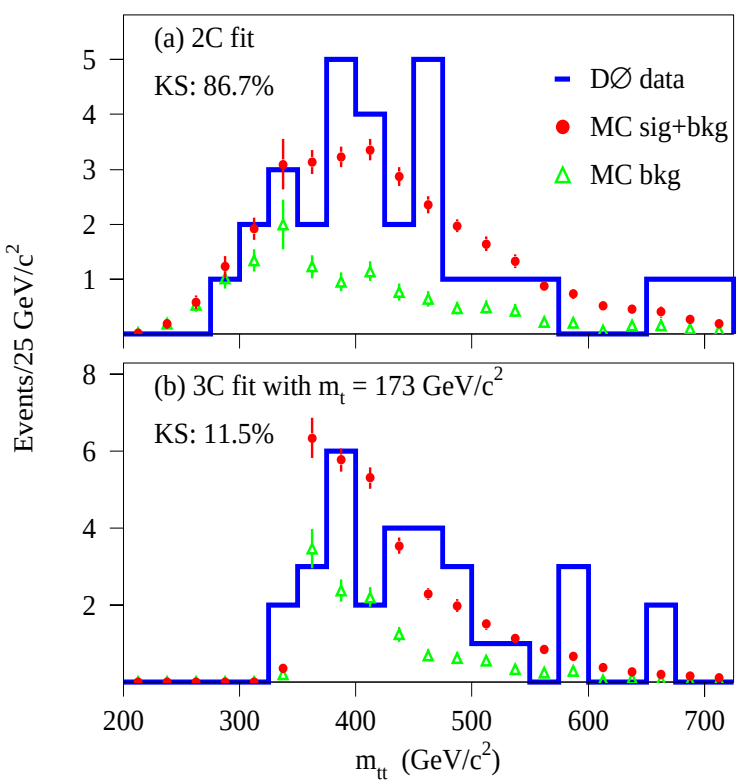
Top-Antitop Mass

- **Unlike the bottom quark, top-antitop are not expected to form bound states due to its short lifetime**

- **However, many models predict the existence of top and antitop resonances**
  - **technicolor gg $\rightarrow \eta_T \rightarrow$ (tt, gg)**
  - **topcolor qq $\rightarrow V_8 \rightarrow$ (tt, bb)**

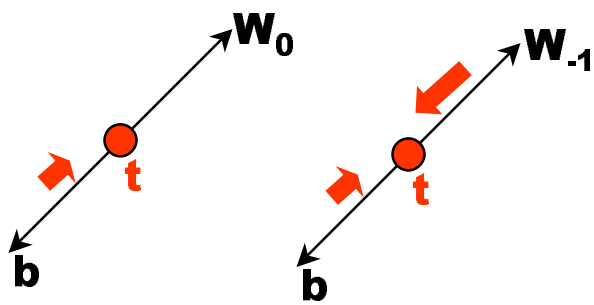
- **Top-antitop invariant mass distribution is a tool for searching for new physics**





W Boson Helicity

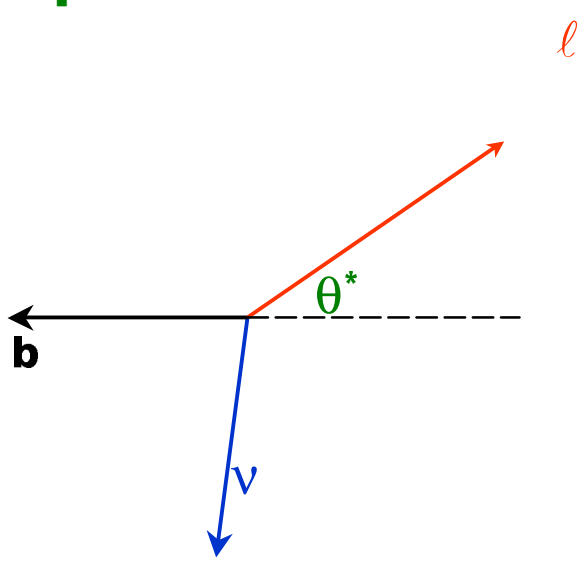
Top quark decays before hadronization via V- A interaction



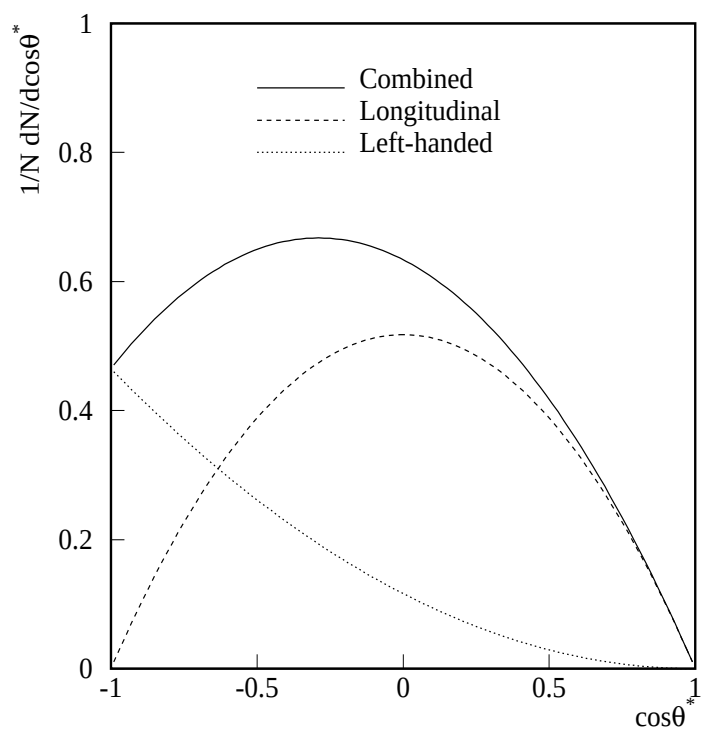
Top quarks can only decay to longitudinal (W_0) or left-hand (W_{-1}) polarized W bosons

In the standard model $F_0 \equiv \frac{W_0}{W_0 + W_{-1}} \approx \frac{m_t^2}{2M_W^2 + m_t^2} \approx 70\%$

W polarizations can be analyzed from the angular or pT distributions of the charged leptons



Top rest frame



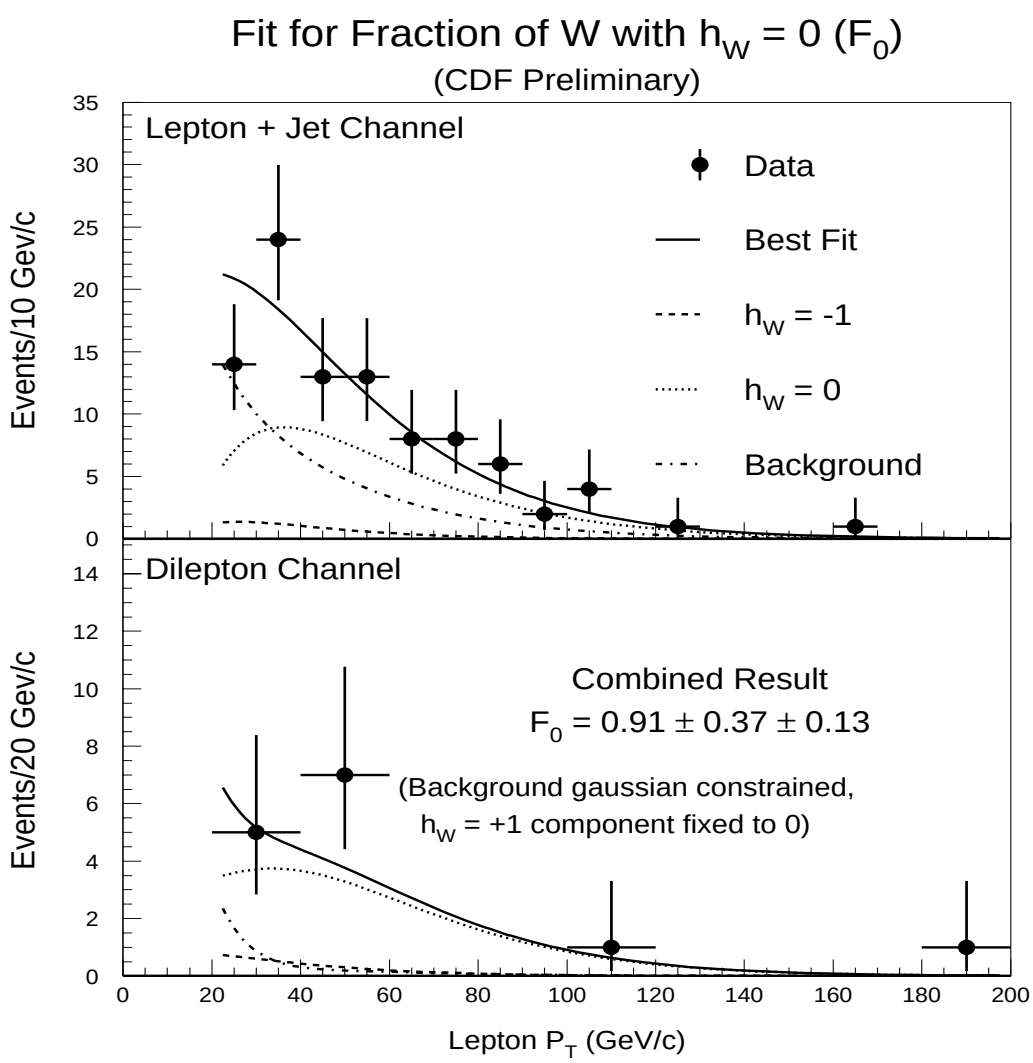
W Boson Helicity

- **Top quark decays provide the first opportunity for studying longitudinally polarized Ws**
- **Non-standard top quark decays may result in different W polarization**

Using dilepton and lepton+jets events, CDF has measured

$$F_0 = 0.91 \pm 0.37(stat) \pm 0.12(syst)$$
$$F_{+1} = 0.11 \pm 0.15(stat) \pm 0.06(syst)$$

CDF, PRL 84, 216 (2000)



CKM Matrix Element $|V_{tb}|$

- $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$ assuming 3 generations and $|V_{tb}|$ is expected to be very close to 1
- no constraints if more than 3 generations
- any departure of $|V_{tb}|$ from 1 indicates physics beyond the standard model

Extract $|V_{tb}|$ from the measurement of R

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Count dilepton and lepton+jets events with zero, single and double b-taggs, CDF has determined:

$|V_{tb}| > 0.75$ @ 95% CL assuming 3 generations

$|V_{tb}| > 0.046$ @ 95% CL without the assumption

In Run IIa with 2 fb^{-1}, $\delta|V_{tb}| \approx 10\%$ benefit from large statistics and improved b-tagging capability

Search for Charged Higgs

- **The standard model with two Higgs doublets will result five Higgs particles**

$$h^0 \quad H^0 \quad A^0 \quad H^+ \quad H^-$$

- **The Higgs sector will have six free parameters**
  - $m_{h^0} \quad m_{H^0} \quad m_{A^0} \quad m_{H^\pm}$
  - $\tan\beta = \dfrac{\upsilon_2}{\upsilon_1}$: the ratio of VEVs
  - α: Higgs mixing angle

- **If charged Higgs bosons are sufficiently light, they can be produced in t $\rightarrow$ Hb decays**
- **The new decay mode with compete with the standard model t $\rightarrow$ Wb mode**
- **Since W and H decay differently** $W \rightarrow \ell\nu,\ q\bar{q}',\quad H \rightarrow \tau\nu,\ c\bar{s},\ Wb\bar{b}$

  t $\rightarrow$ Hb decay will lead to different signatures for top quark pair events

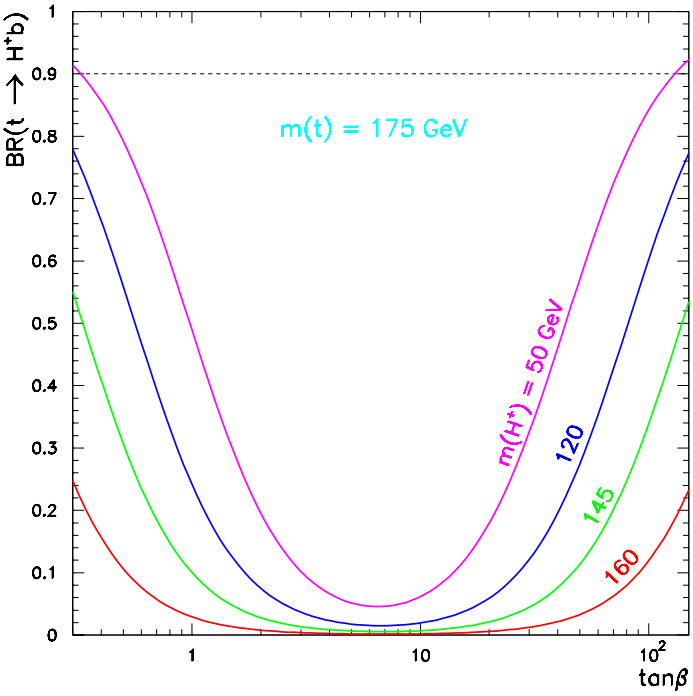
Signature for charged Higgs production:
- **disappearance of standard *WWbb* signature**
- **anomalous τ lepton production**

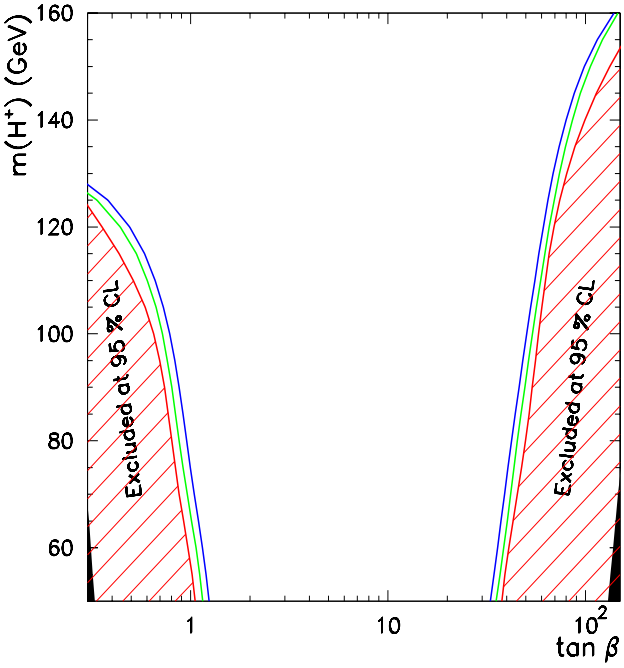
Search for Charged Higgs

Disappearance Search

- The measured top quark pair production cross section agrees with standard model prediction
- Sensitive only to the regions of parameter space with large B(t→Hb)
- Sensitive only to topologies different from WWbb of the SM top quark pair

Both CDF and DØ studied the implication of the cross section measurement on the charged Higgs parameter space

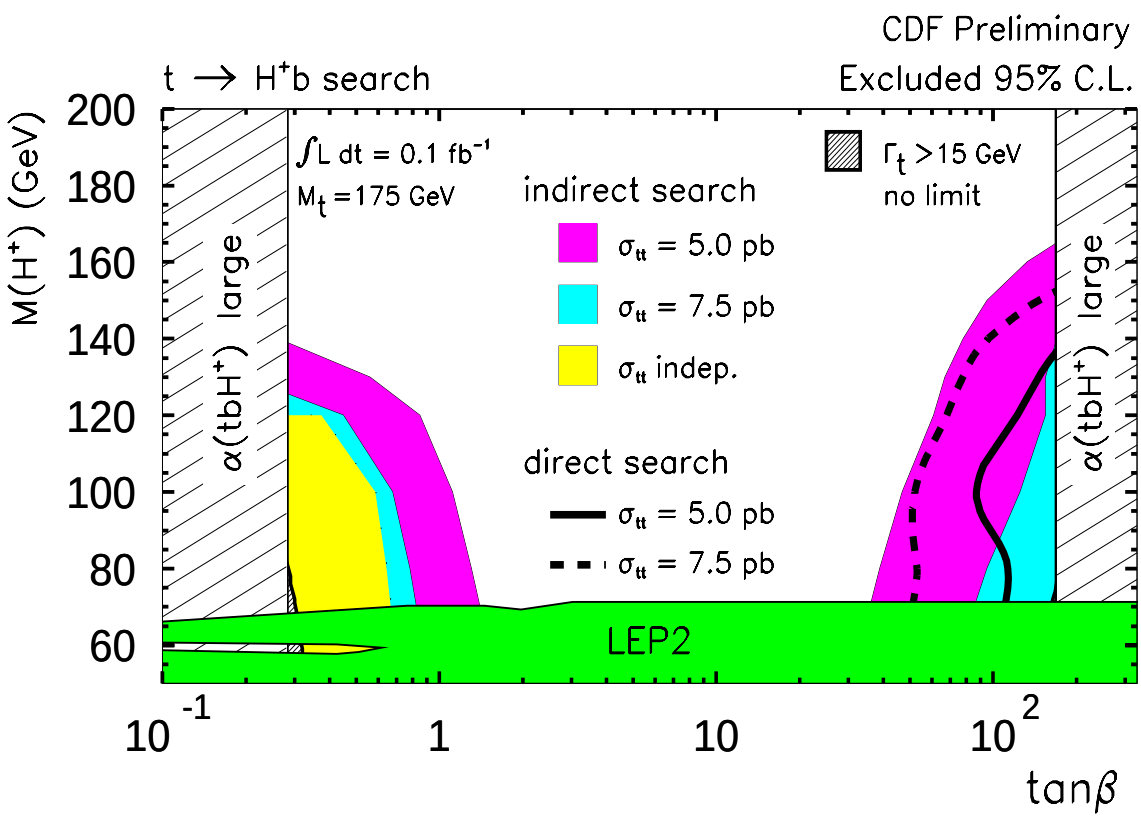




Search for Charged Higgs

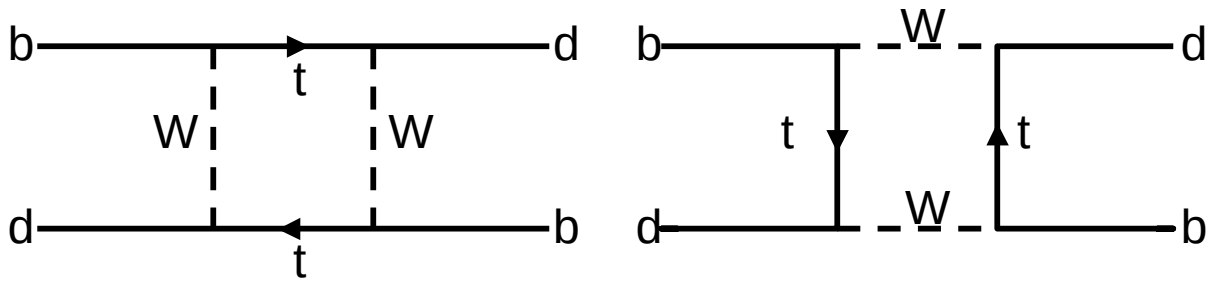
Appearance Search

- **CDF searched for *t*→ *Hb* decay via τ appearance for high tanβ (where *H*→τν)**
  Phys. Rev. D54, 735 (1996)
- **For the τ appearance analyses, τ*jjX* and acoplanar ττ events were searched**
- **The major backgrounds are fake taus, W+jets, Z+jets and WW, WZ, ZZ productions**
- **7 events were observed with 7.4±2.0 events expected. No excess of events**



Heavy Top Quark

- **Besides negative searches, the other indication of a heavy top quark is from the $B^0\overline{B}^0$ mixing measurement by ARGUS and CLEO**



- **Theoretically it was known since early 80s that some super-gravity models require top quark mass to be above 150 GeV**

Consequences of a heavy top

- **Yukawa couplings:** $\lambda_t = \frac{\sqrt{2}m_t}{v} \approx 1$ **for top quarks and**

  $\lambda_e = \frac{\sqrt{2}m_e}{v} \approx 3\times 10^{-6}$ **for electrons**

- **Generates electroweak symmetry breaking through radiative correction**

Is it "Why the top quark is so heavy ?" Or
Is it "Why other particles are so light ?"

Top Physics in Run II

Expect to have a factor of 50 increase in top quark sample in Run IIa

- Improved measurement of top quark mass and pair production cross section
- Measure top quark decay branching ratios and test of standard model predictions
- Study kinematic distributions
  - spin correlation
  - top polarization
  - transverse momentum
  - mass of top quark pair
  - ....
- Observation of single top quark production and determination of its decay width
- Search for new physics from top quark decays

Hope to answer the question
"Does the top quark play a role in electroweak symmetry breaking?"

A rich top physics program!