The Discovery of the Top Quark

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Overview

- Standard Model Framework
- The Role of the Top Quark
- The Discovery of Top
- What We Know About Top Today
  - Top Quark Mass
  - Production and Decay Rates
  - Single Top
- Prognostications

Guelph Colloquium, 6 Feb 2001

The Standard Model

The ingredients of the SM are

- 12 fermions
  - 6 quarks (u, d, s, c, b, t)
  - 6 leptons (e^-, ν_e, μ, ν_μ, τ, ν_τ)
- 3 electroweak bosons (W^+, W^-, Z°, γ)
- 8 gluons to describe the strong force
- ?? to describe gravity

Enormously successful paradigm since ~ 1975

- Predicted rich phenomenology
- Accurate! (eg. $\delta_{M_z}/M_z \sim 8 \times 10^{-5}$)

Predicted existence of top quark in late 1970's

- Higgs boson the only other "essential" missing element

Why a Top Quark?

In 1977, Lederman et al. reported a new resonance

- Mass of 9.54 ± 0.04 GeV/c^2
- Decayed to $\mu^+\mu^-$ pairs

$\Rightarrow$ A fifth quark

- e^+e^- production rate $\Rightarrow Q = -1/3$

Studies implied that the b quark had a missing partner

- "Flavour-changing neutral current" decays didn't occur
  - decays like $b \to \mu^+\mu^- d$ not observed
- $e^+e^- \to b\bar{b}$ scattering suggested an $SU(2)$ state

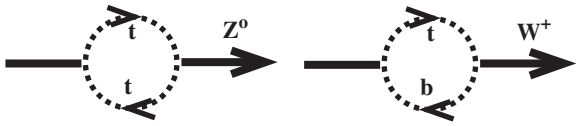
$\Rightarrow$ A sixth quark, known as "top" or "truth"

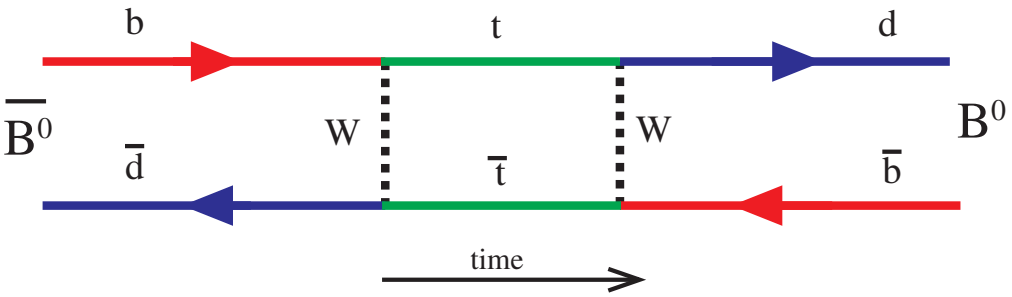
- Would have $Q = +2/3$

The Top Quark in the Standard Model

The SM "needs" a heavy top quark

- Loop effects in SM driven by M_{top}
  - W/Z boson mass ratio
  - $b - \overline{b}$ mixing





However, exact value of M_{top} not constrained

- In 1983, knew it had to be large ($\gtrsim$ 20 GeV/c^2)
- Searches limited by collider centre-of-mass energies

SM Top Quark Phenomenology

Top quarks decay via the weak force

- Predict $\sim 100\%$ $t \to W^+ b$
- For heavy top ($M_{top} \gtrsim 100 - 120$ GeV/c^2), decays before it hadronises

Can be viewed as "pure" β decay

$$\begin{aligned} \Gamma_{\text{top}} &= \frac{G_F M_t^3}{8\sqrt{2}\pi}\left(1-\frac{M_W^2}{M_t^2}\right)^2\left(1+2\frac{M_W^2}{M_t^2}\right) \\ &\sim 175 \text{ MeV} \left(\frac{M_t}{M_W}\right)^3 \sim 2 \text{ GeV} \end{aligned}$$

- Toponium ($t\bar{t}$) doesn't have time to form
- T mesons ($t\bar{q}$) $\sim$ degenerate (if they had time...)

Decay dominated by "longitudinal W^+"

- Means the W^+ prefers helicity 0
- Result of large top and W^+ mass

The Hunt for the Top Quark

SM didn't tell us the top quark mass

- Search for top quark production in e^+e^- and $p\bar{p}$
  - Rate decreases sharply with M_{top}
  - Production and decay signature change with mass
    - $p\bar{p} \to W \to t\bar{b}$
    - $e^+e^- \to t\bar{t}$
    - $p\bar{p} \to t\bar{t} \to W^+ b\, W^- \bar{b}$

UA1 experiment at CERN had one "false call"

- Observed a handful of $W \to t\bar{b}$ candidates in 1983
  - Turned into a limit of $M_{top} > 42$ GeV/c^2 by 1985
- A search by CDF in 1988-89 found $M_{top} > 77$ GeV/c^2

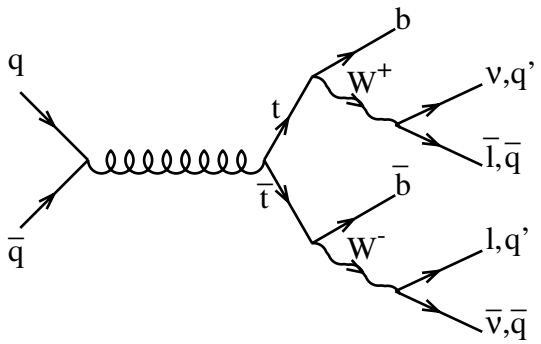
By 1992, had new measurements of M_Z and M_W

- SM predicted top quark with $M_{top} \gtrsim 140$ GeV/c^2
- Only place to look was in high-energy $p\bar{p}$ collisions
- Two experiments
  - DØ and Collider Detector at Fermilab (CDF)

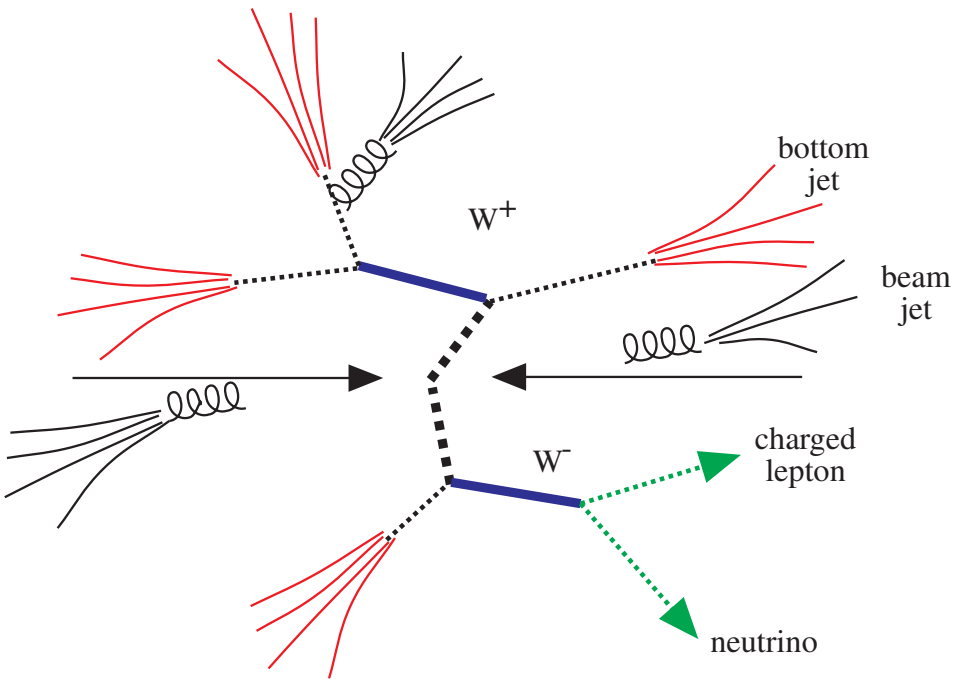
Reconstructing Top

Since top is pair-produced and β decays

- Expect to see 6 final state particles



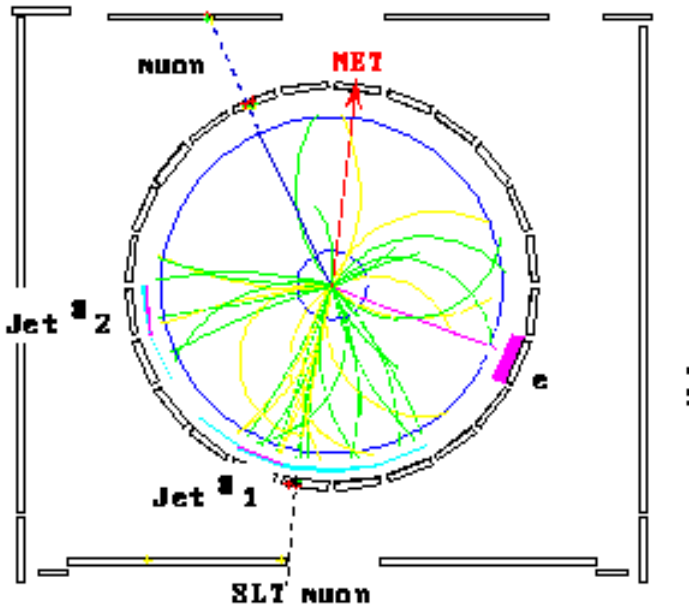
Life is normally not that easy – in reality:



Identifying Top Decays in $p\bar{p}$ Collisions

In order to identify top candidates

- Search for $W \to l\nu_l$ candidate
  - Electron or muon with $P_T > 20$ GeV/c
  - Missing transverse energy $\not\!\!E_T > 20$ GeV
- Search for at least one b jet
  - Most effective tool is to find a secondary vertex
- Some evidence of other W in event
  - Either two more jets or another lepton

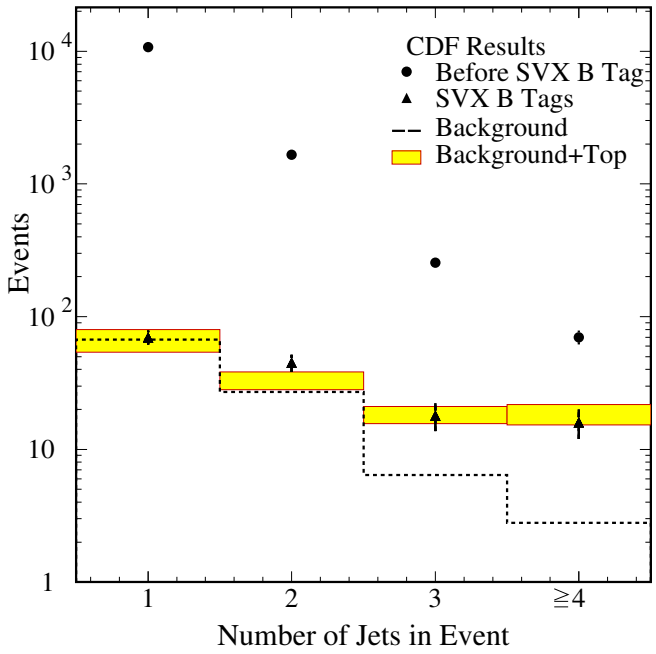


Strategy for Detection

Identify events with a $W^+ \to l^+\nu_l$ signature

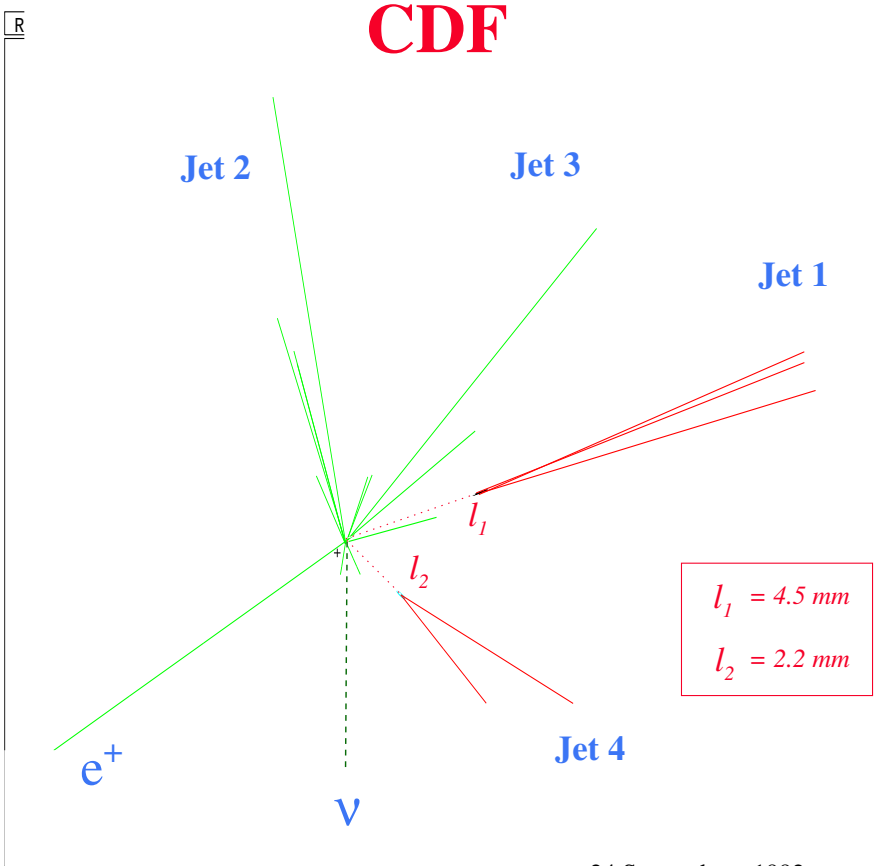
- Require evidence of a second W boson
  - $W \to e^+\nu_e$ or $\mu^+\nu_\mu$
  - $W \to q'\bar{q}$
- At least one more jet "tagged" as a b quark jet

Look for an excess of such events



Convincing "Smoking Gun" Events

$t\bar{t}$ Event
SVX Display
CDF



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

24 September, 1992
run #40758, event #44414

Discovery of Top

Hints of top production appeared as early as 1993

- CDF published a 61 page PRD in Sep 1994
- Gave "cagey" label to the reports
  - "Evidence for top quark production..."
- DØ's analysis not as definitive

With a factor of two more data, result was unequivocal

- April 1995, both collaborations announced discovery
- Confirmed SM predictions – $M_{top} \sim 170 - 190$ GeV/c^2
- Gave us a "free quark" system to study

  $\Rightarrow$ New frontier in particle physics

Status of Collider Experiments

CDF and DØ collected ~ 110 pb^{-1} of data in 92-96

- 1.8 TeV $p\bar{p}$ collisions
- Collected events with
  - High P_T leptons ($P_T \gtrsim 10$ GeV/c)
  - $\not\!\!E_T > 25$ GeV
  - High P_T jets ($P_T \gtrsim 100$ GeV/c)

Studies have strengthened top quark interpretation

- Different techniques used to look at the same data
  - Kinematic distributions
  - Neural network approaches
- Verified that all decay modes appear to be OK
  - See reasonable signals in τ lepton final states
  - All hadronic modes are also understood

The Status of Top Today

CDF has now detected top in virtually all decay modes

- Lepton + Jets mode (for mass analysis)
  - lepton $P_T > 20$ GeV/c and $\not\!\!E_T > 20$ GeV
  - ≥ 3 jets, $E_T > 15$ GeV and $|\eta| < 2$
  - Require 1 b-tagged jet OR a 4th jet with $E_T > 15$

  $\Rightarrow$ 76 candidates (expect 31 ± 7 bkg)

- Dileptons
  - 2 leptons with $P_T > 20$ GeV/c
  - Remove Drell-Yan and Z° background

  $\Rightarrow$ 9 candidates (2.4 ± 0.5 events bkg)

- All hadronic decays
  - between 5 and 8 jets ($E_T > 15$ GeV and $|\eta| < 2.0$)
  - $\sum E_T > 300$ GeV + additional kinematic cuts

  $\Rightarrow$ Observe 187 b-tagged jets (142 ± 11 expected bkg)

What are the Interesting Top Properties?

- Top Quark Mass
  - SM constrains it to M_W/M_Z
  - Important consistency check of theory

- Top Quark Production Cross Section
  - Predicted by QCD with less uncertainties than σ_b
  - Look for single top production

- Top Quark Decay Rates
  - Measured $t \to W^+b/t \to W^+q$
  - Look for $t \to H^+b$

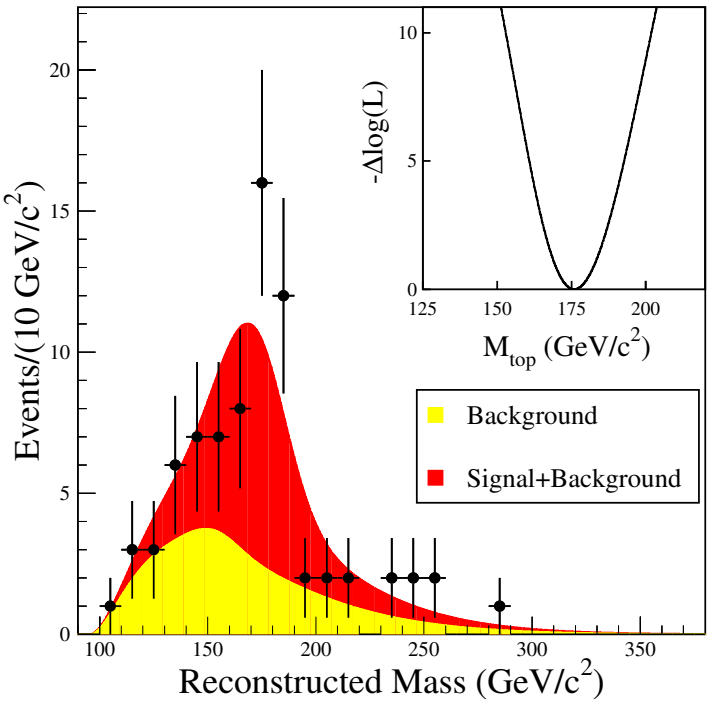
- Top Quark Decay Kinematics
  - SM expects decay to be polarized
  - Have made first measurement of polarization

- Single Top Production

Top Quark Mass

Measurements now limited by statistical uncertainties

- Overall systematic uncertainty is ~ 5 GeV/c^2
  - Dominated by uncertainties in soft gluon contributions and energy scale
- Run I statistics limit systematic uncertainty

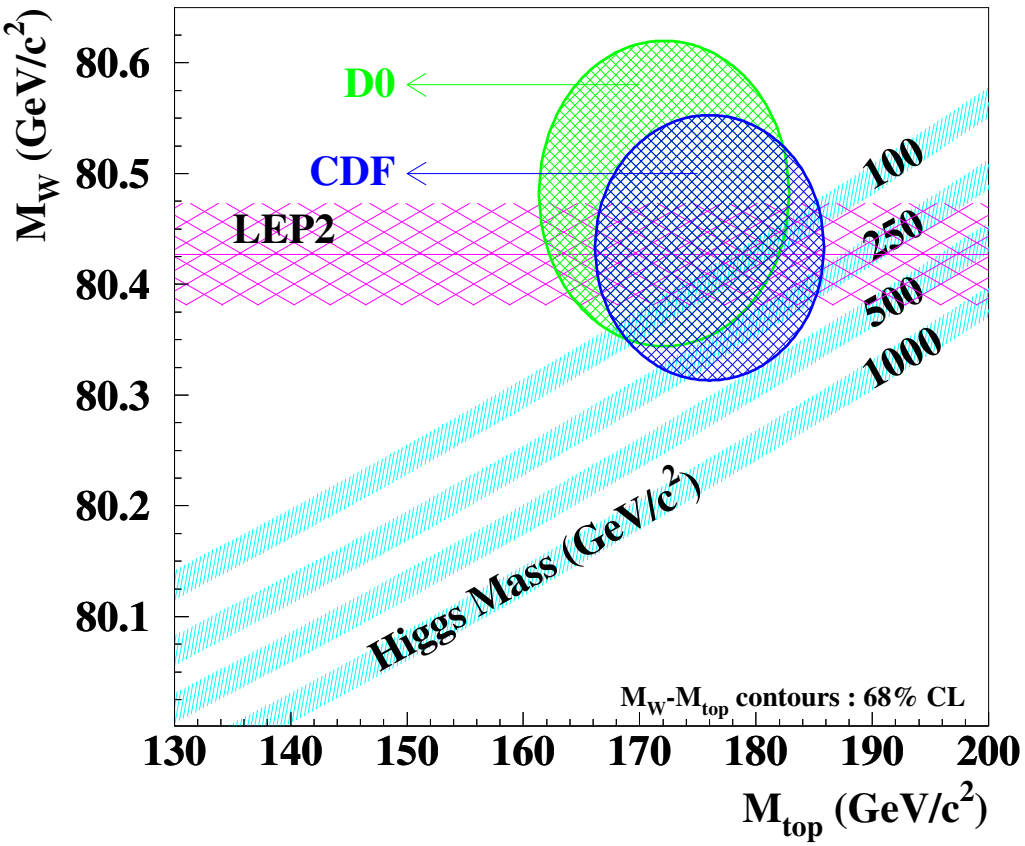


The final Run I values are

$$M_{top} = 176.1 \pm 6.6 \text{ GeV c}^2 \text{ (CDF)}$$
$$M_{top} = 172.1 \pm 7.1 \text{ GeV c}^2 \text{ (DØ)}$$
$$M_{top} = 174.3 \pm 5.1 \text{ GeV c}^2 \text{ (RunI)}$$

Latest W boson mass results

M_W	=	80.433 ± 0.079 GeV c^2	CDF
M_W	=	80.482 ± 0.091 GeV c^2	D0
M_W	=	80.427 ± 0.046 GeV c^2	LEP2

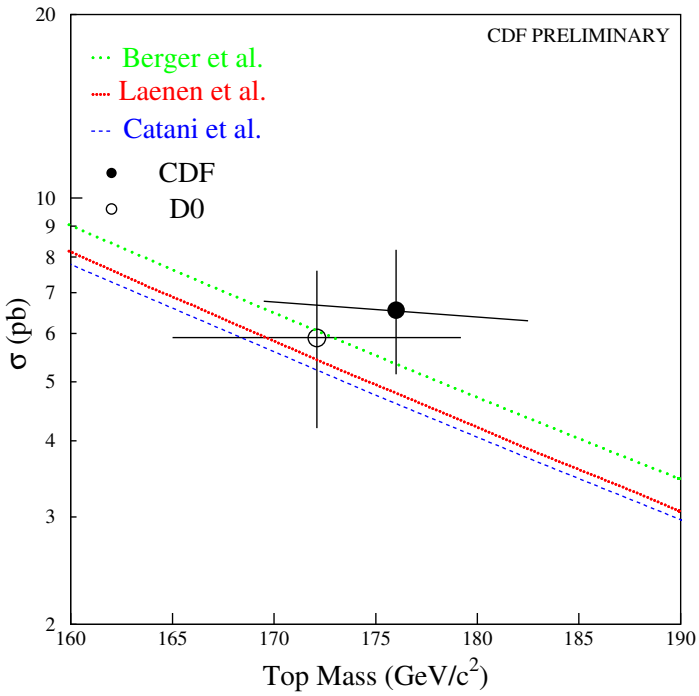


Top Quark Production Cross Section

The cross section obtained by a fit to

- Lepton + jets, dileptons and all hadronic event rates
- Depends on M_{top} because of acceptance
- Recent improvement is more accurate b-tagging efficiency

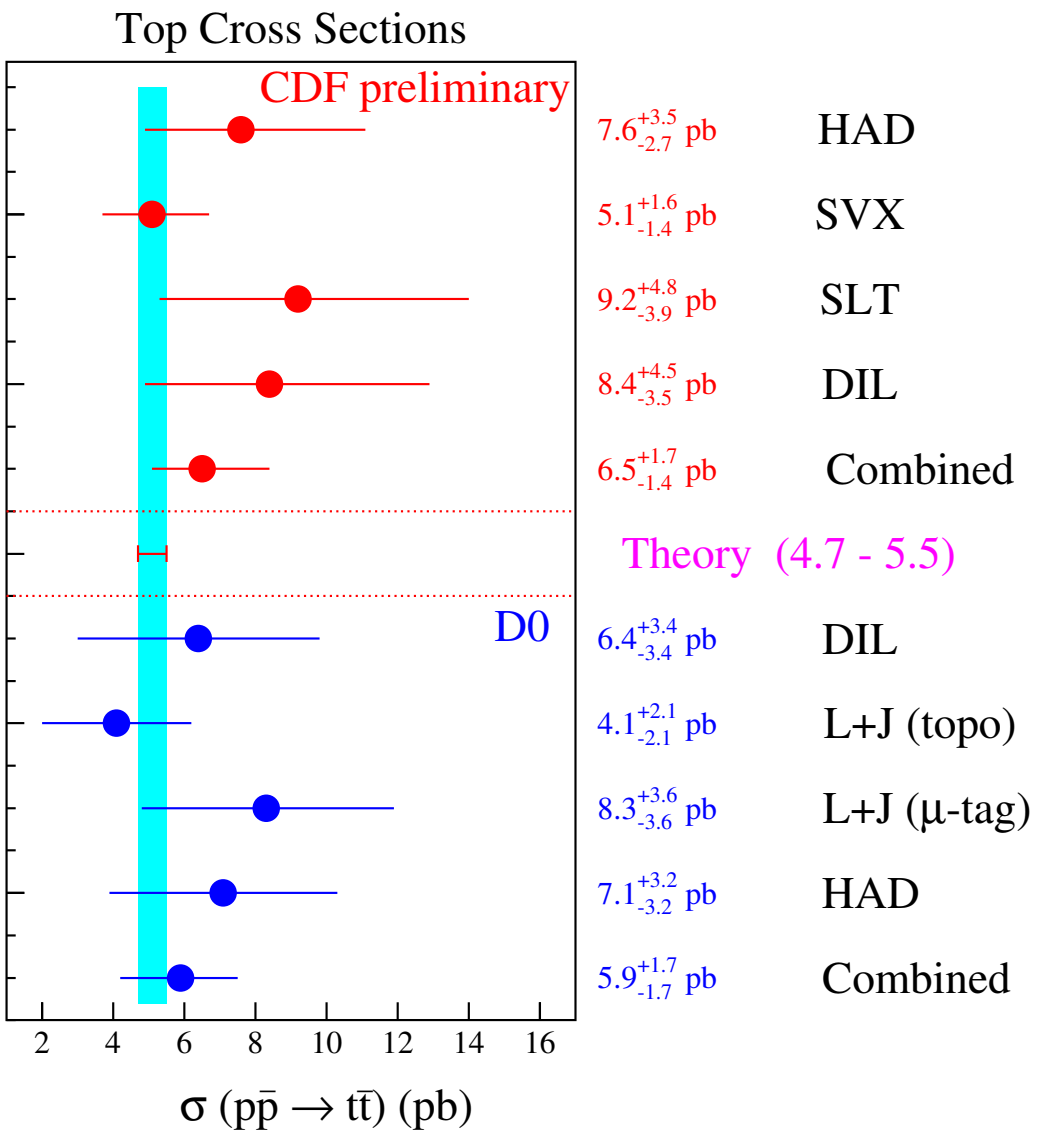
$$\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4} \text{ pb}$$



- Theory predictions range from 4.7 to 5.5 pb

Comparison with DØ

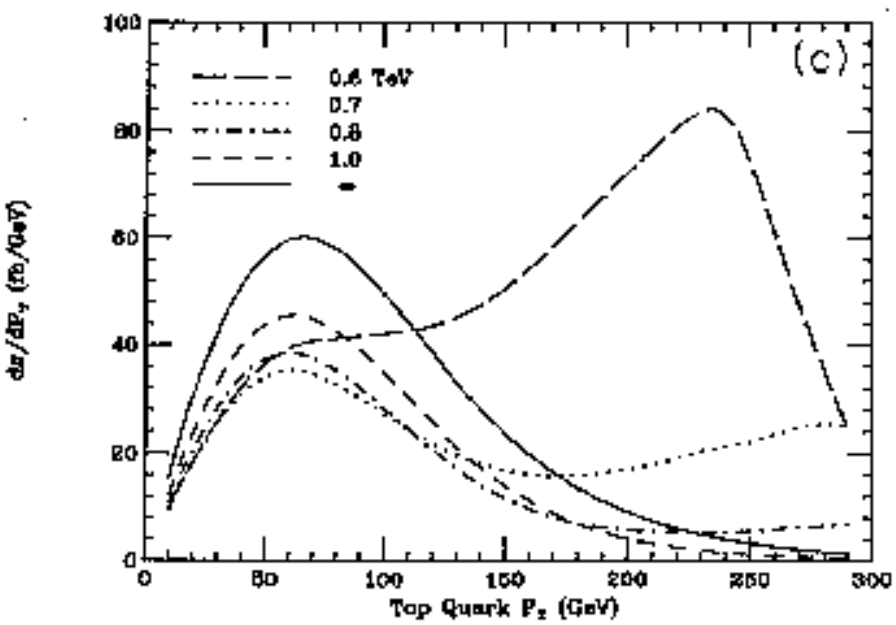
Measurements by DØ also quite consistent



Top Quark Transverse Momentum

SM predicts top quarks produced "back-to-back"

- Broad P_T distribution – $< P_T > \sim M_{top}/2$
- Non-SM predictions can be quite different
  - Can test models (such as Top colour or ADD)



Limited statistics and resolution present challenge

- Produce a set of confidence limits on $\frac{d\sigma_t}{dP_T}$
- Limited to large bins ($\Delta P_T = 75$ GeV/c)

Event Selection

Use the "standard" lepton + jets event selection:

- Single isolated $e(\mu)$ having $P_T > 20$ GeV/c and $|\eta| < 1.0$
- $\not\!\!E_T > 20$ GeV
- ≥ 4 jets, 3 with $E_T > 15$ GeV and $|\eta| < 2.0$
  - fourth with $E_T > 8$ GeV, $|\eta| < 2.4$
- To increase signal significance, require that

$$N_{\text{jet15}} \geq 4 \text{ the or } N_{tag} \geq 1$$

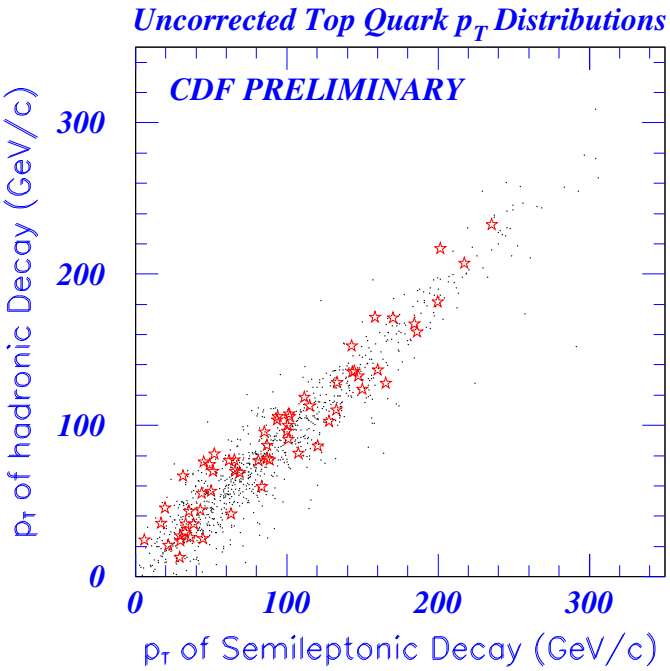
Kinematically fit event, constraining $M_{top} = 175$ GeV/c^2

- Require $\chi^2 < 10$

$\Rightarrow$ Left with 61 events

Measurement of P_T

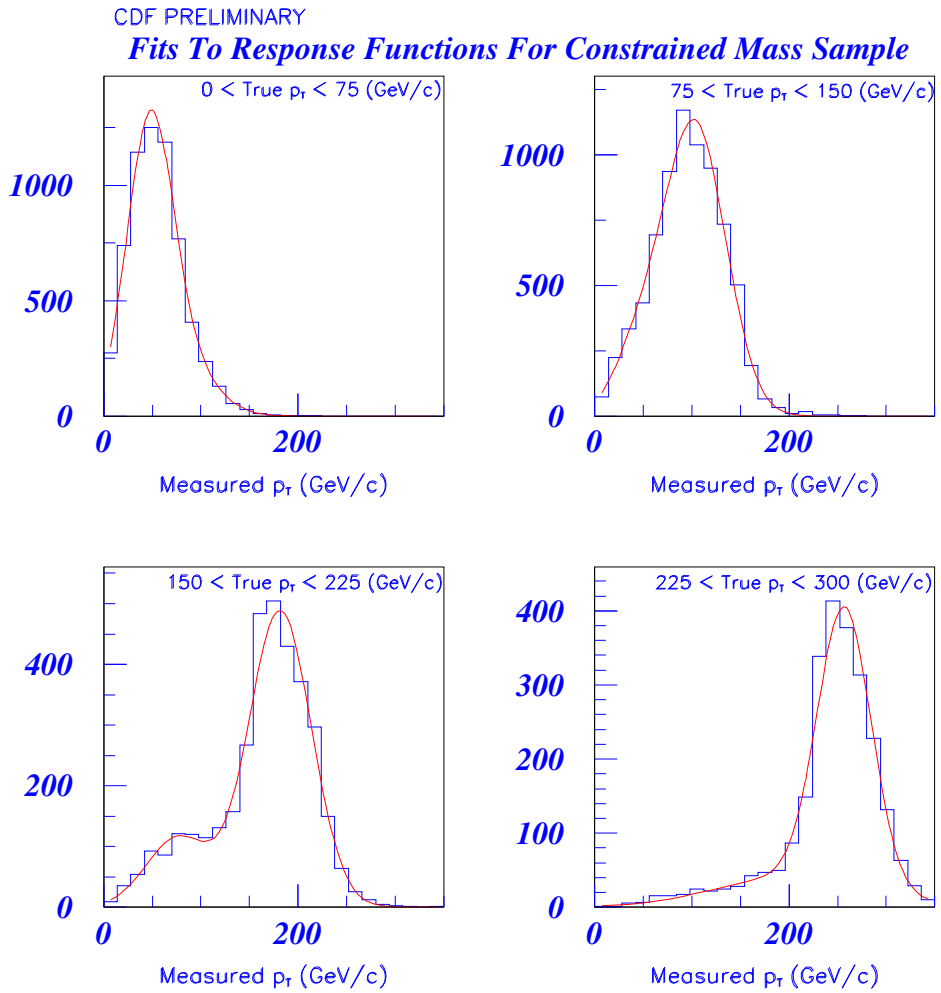
Measurements on lepton-side and jet-side are strongly correlated!



- Make measurement using only jet-side top quarks

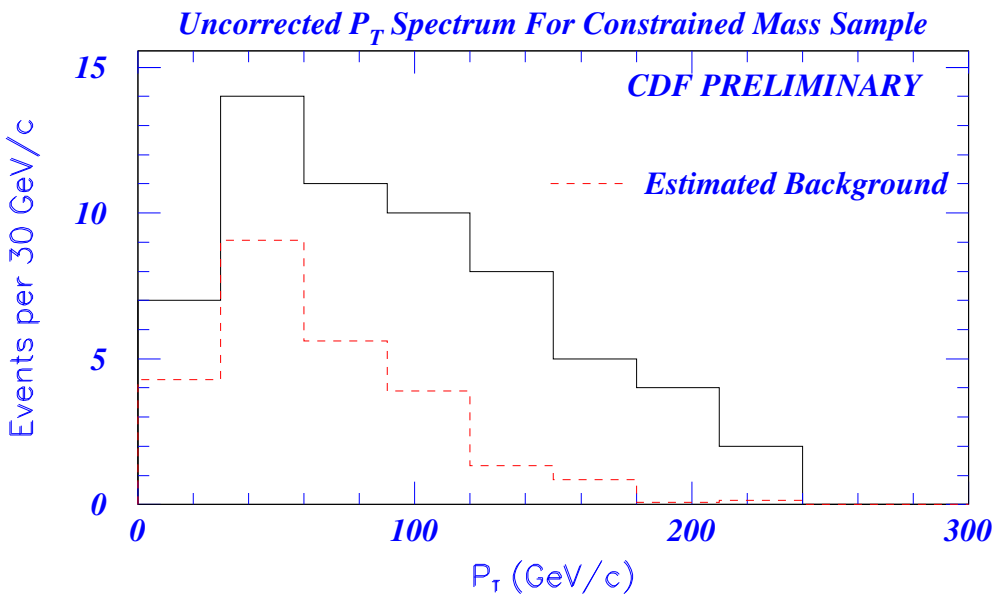
P_T Response Functions

Measured P_T smearing using MC/detector simulation



- Use standard HERWIG MC calculations
- Most smearing arises from incorrect jet assignments

Uncorrected P_T Distribution



- 61 events pass selection criteria
- Background distribution normalized to estimated rate
  - We estimate $N_{bgd} = 31.9 \pm 4.6$ events

Resulting Fitted P_T Distribution

Perform unbinned likelihood fit

- Include four response functions and bkg shapes
- Fit tagged and untagged events with different templates
- Use "bootstrap" technique to minimize assumptions about shape of P_T spectrum within each true bin
- Define

$$R_i \equiv \frac{\text{fraction in } i\text{th bin}}{\sigma_{t\bar{t}}}$$

Apply P_T-dependent acceptance correction

- Acceptance increases with P_T

$$\begin{aligned} R_1 &= 0.21^{+0.22}_{-0.21} \\ R_2 &= 0.45^{+0.23}_{-0.23} \\ R_3 &= 0.34^{+0.14}_{-0.12} \\ R_4 &= 0.000^{+0.031}_{-0.000} \end{aligned}$$

Confidence Level Interval on R_4

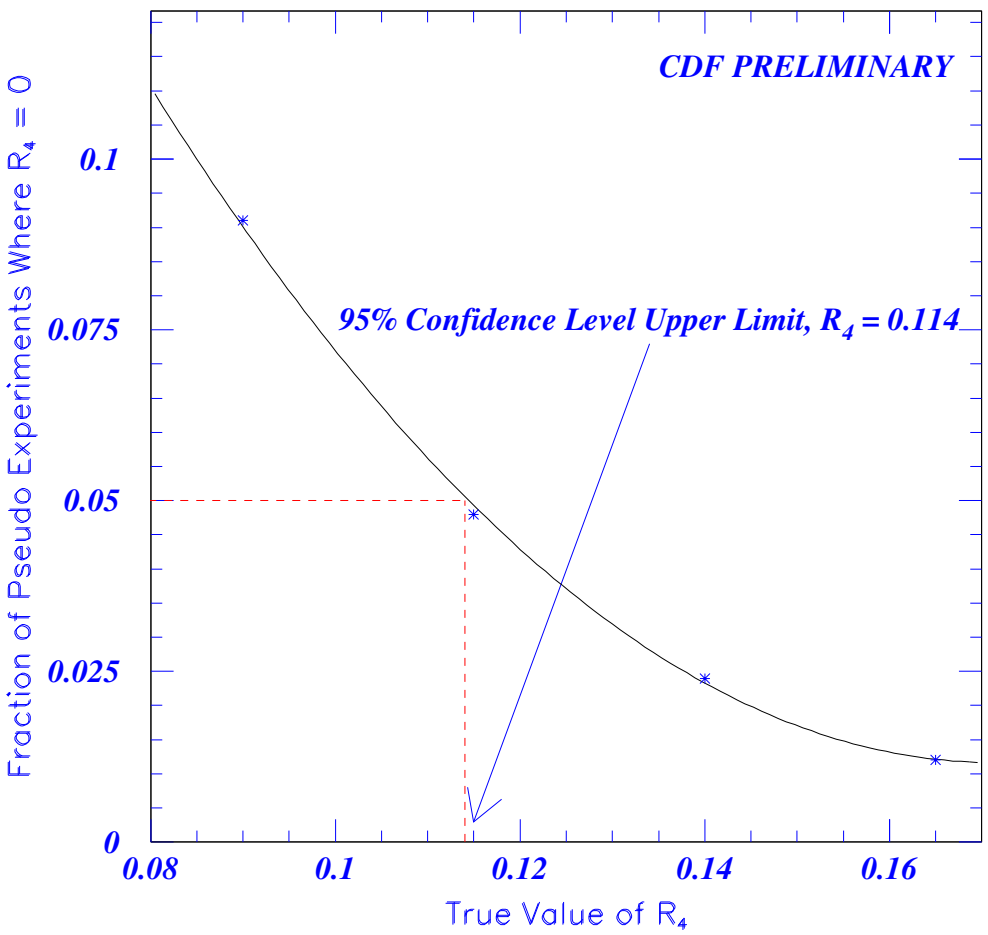
Obtain $R_4^{\text{fit}} = 0$ (fraction of top with $P_T > 225$ GeV/c)

- Use non-Bayesian technique to infer "true" size of R_4
- Set a 95% CL limit using a MC technique
  - Analyze samples of MC events with varying R_4^{true}.
  - Smear R_4^{true} in each with Gaussian distribution with a width equal to systematic uncertainty
  - Determine value of R_4^{true} where only 5% of the MC samples have $R_4^{\text{fit}} = 0$

CDF PRELIMINARY

Systematic Effect	$\delta(R_4)$
Background Model	± 0.0028
Jet Energy Scale	$^{+0.0007}_{-0.0042}$
No Initial State Radiation	± 0.0045
Final State Radiation	± 0.0095
Flat P_T Spectrum	± 0.0157
$m_t = 180$ GeV	-0.0160

95% Confidence Level Upper Limit



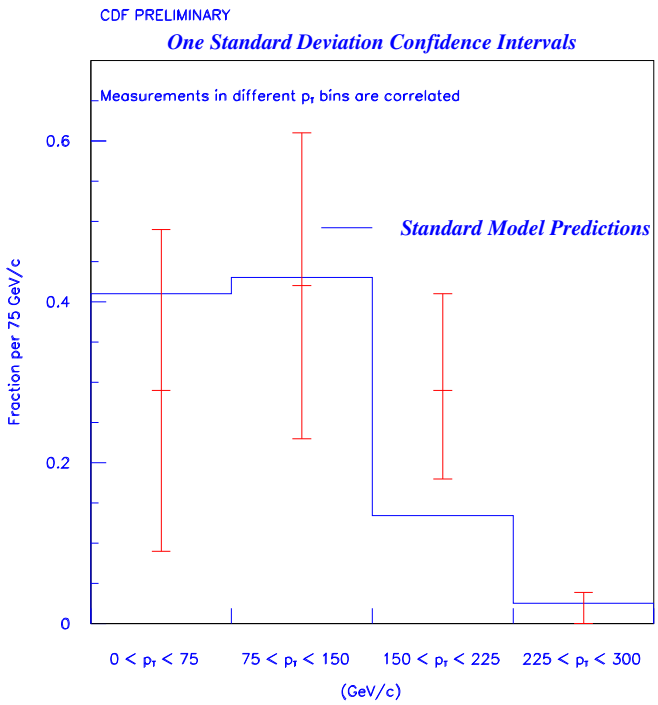
Agrees with result obtained by integrating the likelihood function

- Including systematics, $R_4 < 0.16$ at 95% CL

Top Quark Differential Cross Section

$$R_1 + R_2 = 0.66^{+0.17}_{-0.17}(\text{stat})^{+0.06}_{-0.06}(\text{syst})$$

$$R_4 < 0.16 \text{ at } 95\% \text{ C.L.}$$



P_T Bin	Measured Fraction of Top Quarks
$0 < P_T < 75$ GeV/c	$R_1 = 0.21^{+0.22}_{-0.21}(\text{stat})^{+0.10}_{-0.08}(\text{syst})$
$75 < P_T < 150$ GeV/c	$R_2 = 0.45^{+0.23}_{-0.23}(\text{stat})^{+0.04}_{-0.07}(\text{syst})$
$150 < P_T < 225$ GeV/c	$R_3 = 0.34^{+0.14}_{-0.12}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$
$225 < P_T < 300$ GeV/c	$R_4 = 0.000^{+0.031}_{-0.000}(\text{stat})^{+0.019}_{-0.000}(\text{syst})$

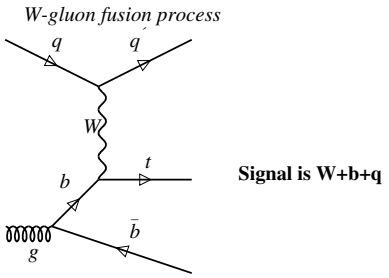
Single Top Production

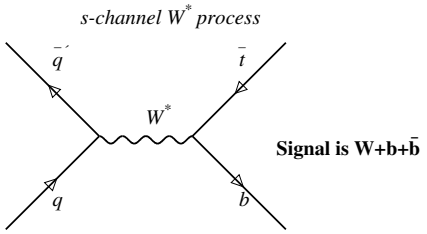
Single top production is a much lower rate process

- Sensitive to Γ_t
- Also could have contributions from non-SM sources

There are two primary SM production processes

1. t-channel $W-g$ fusion $\Rightarrow W^+bq$ final state
2. s-channel W^* process $\Rightarrow W^+b\bar{b}$ final state





- Predicted cross sections are 1.7 ± 0.3 and 0.7 ± 0.1 pb

Search Technique

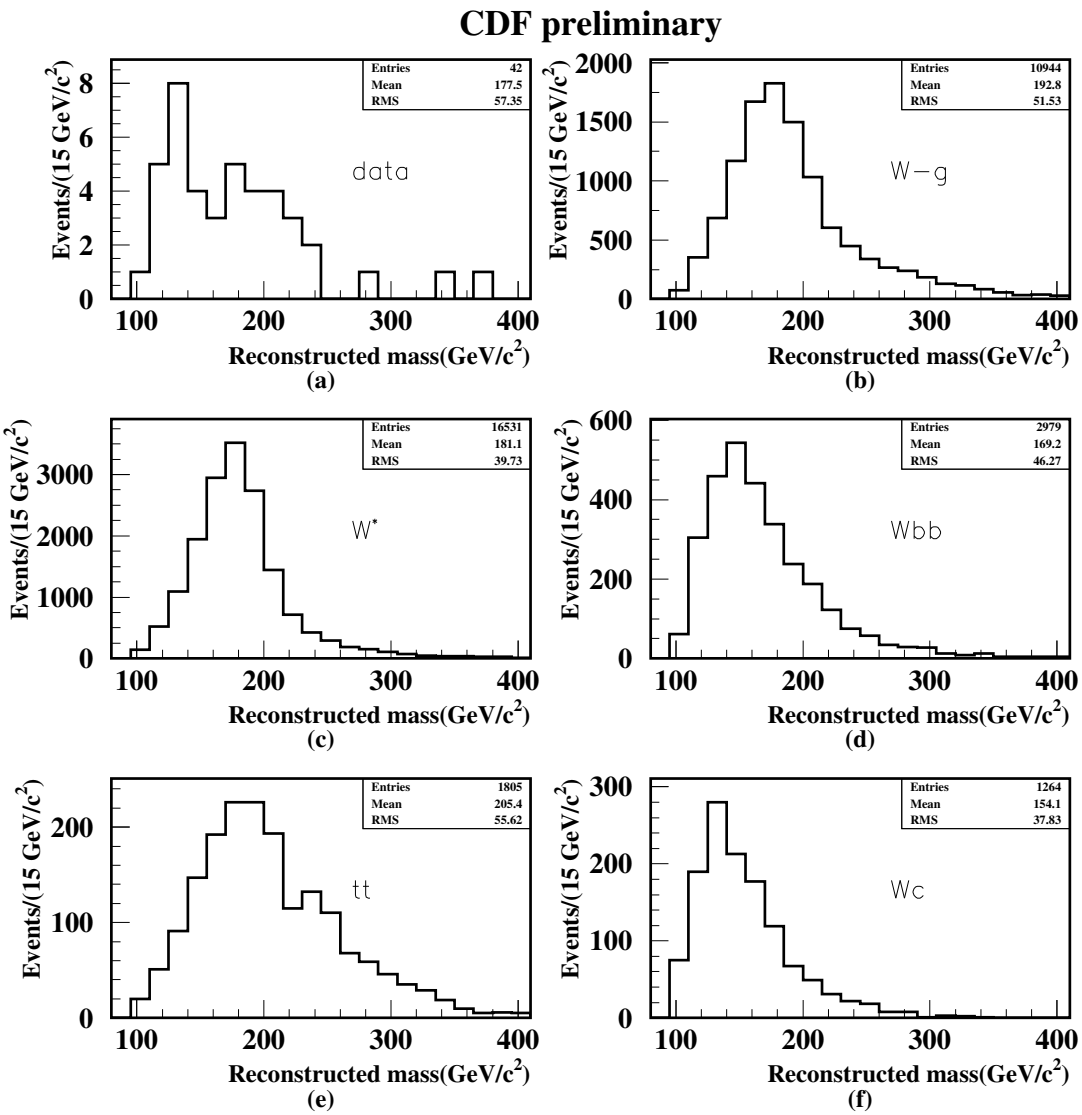
Kinematics of production processes different

- Use the same selection for both processes
  - 1, 2 or 3 jets with $E_T > 15$ Gev and $|\eta| < 2.0$
  - At least one b-tagged jet
  - Require $140 \leq M_{top} \leq 210$ GeV/c^2
- Fit H_T distribution with signal and background terms

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

	W^*	W-gluon
σ_{theory} (pb)	0.73 ± 0.10	1.7 ± 0.3
Integrated luminosity (pb^{-1})	106 ± 4	106 ± 4
$W + n$ jet acceptance (%)	4.5 ± 0.7	6.7 ± 1.0
SVX b-tag efficiency (%)	37.5 ± 3.1	24.8 ± 2.0
Number of expected events	1.3 ± 0.3	3.0 ± 0.6

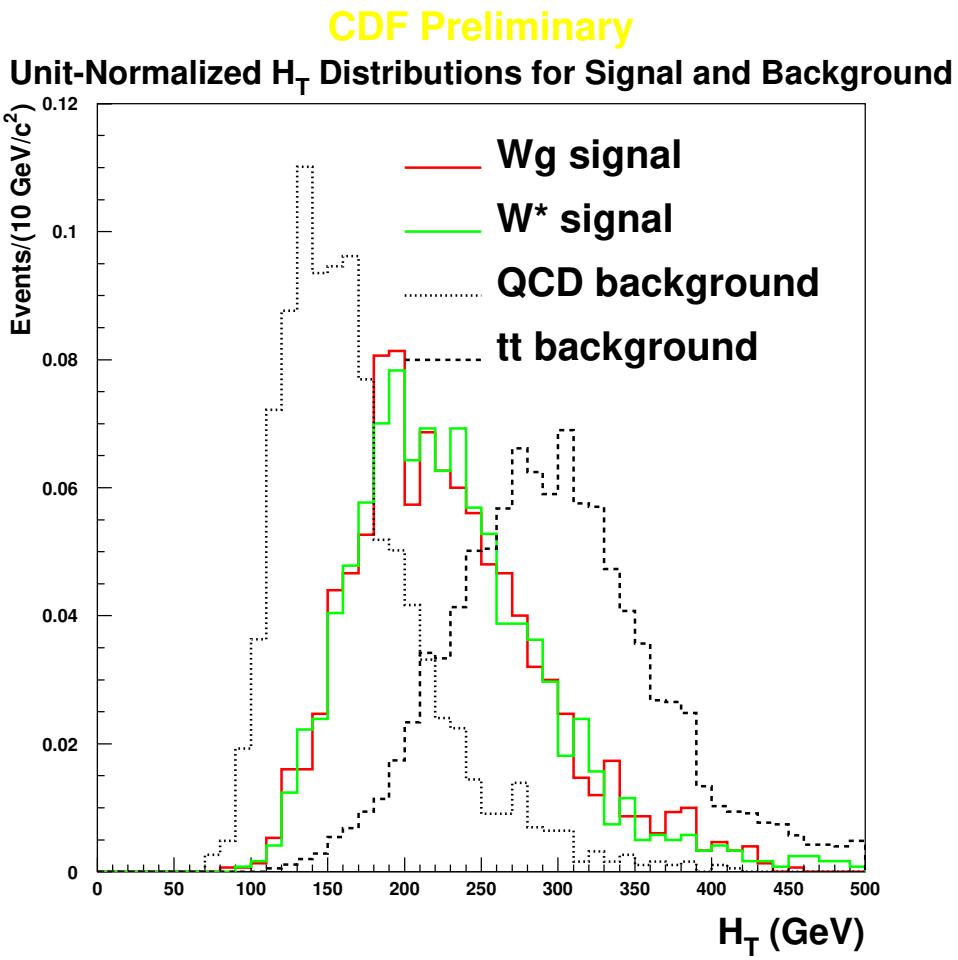
Top Mass Reconstruction



H_T Reconstruction

The variable H_T is an effective discriminator

- QCD Background
- $t\bar{t}$ background
- Single top signal



Results of Search

Observed 65 events in this sample

- Largest single background are mistags
  - $t\bar{t}$ itself is a problem now

Process	Event Yield
Mistags	25.9 ± 7.5
$Wb\bar{b} + Wc\bar{c}$	28.7 ± 7.5
Wc	17.2 ± 6.2
Non-W	12.1 ± 4.1
Miscellaneous	5.1 ± 0.9
After M_t cut	54 ± 11
$t\bar{t}$	8.4 ± 2.7
W-gluon	3.0 ± 0.6
W^*	1.3 ± 0.3
Total expected	67 ± 11
Observed	65

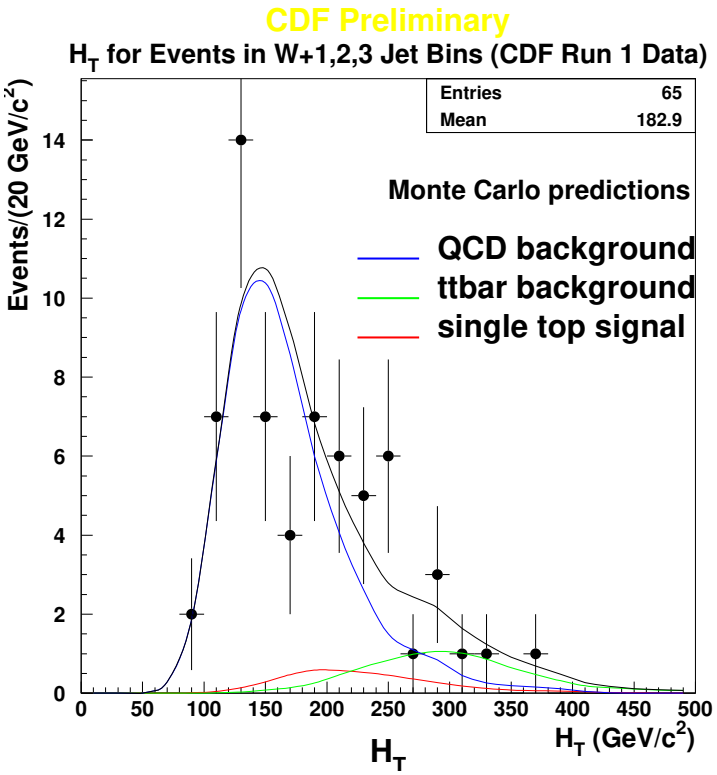
Not yet sensitive to SM single top rate

- Can set limits on total single top rate

Single Top Production Cross Section Limits

Use H_T distribution to fit signal and background shapes

- Set upper limit using a Bayesian technique
- Fit gives $\sigma_t < 13.5$ pb at 95% CL



Still well away from SM rate

- Can conclude that there is no huge anomaly
- It is a feasable measurement for Run II
  - Can get $S/N = 2.9$ on $W + 2,3$ jet sample

Run II Forecasts

Run II will start this summer at $\sqrt{s} = 2.0$ TeV

- CDF had an "engineering run" (partial SVX II) last fall
- Physics running will commence next month 2001

Will be worth the wait

- Begin with ~ 3 fb^{-1}/year per detector
- Finish up with ~ 5 fb^{-1}/year
- Literal "Top Factory" with
  - 300 dilepton events
  - 3000 tagged lepton+jet events
  - 1500 events in "mass sample"

Top Physics Goals in Run II

Mass analysis uncertainties scale with statistics

- Can expect $\delta M_t \sim 3.0$~GeV/c^2
- With $\delta M_W \sim 40$ MeV/c^2

$$\frac{\delta M_{Higgs}}{M_{Higgs}} \sim 40\%$$

- Powerful "pointer" for LHC searches

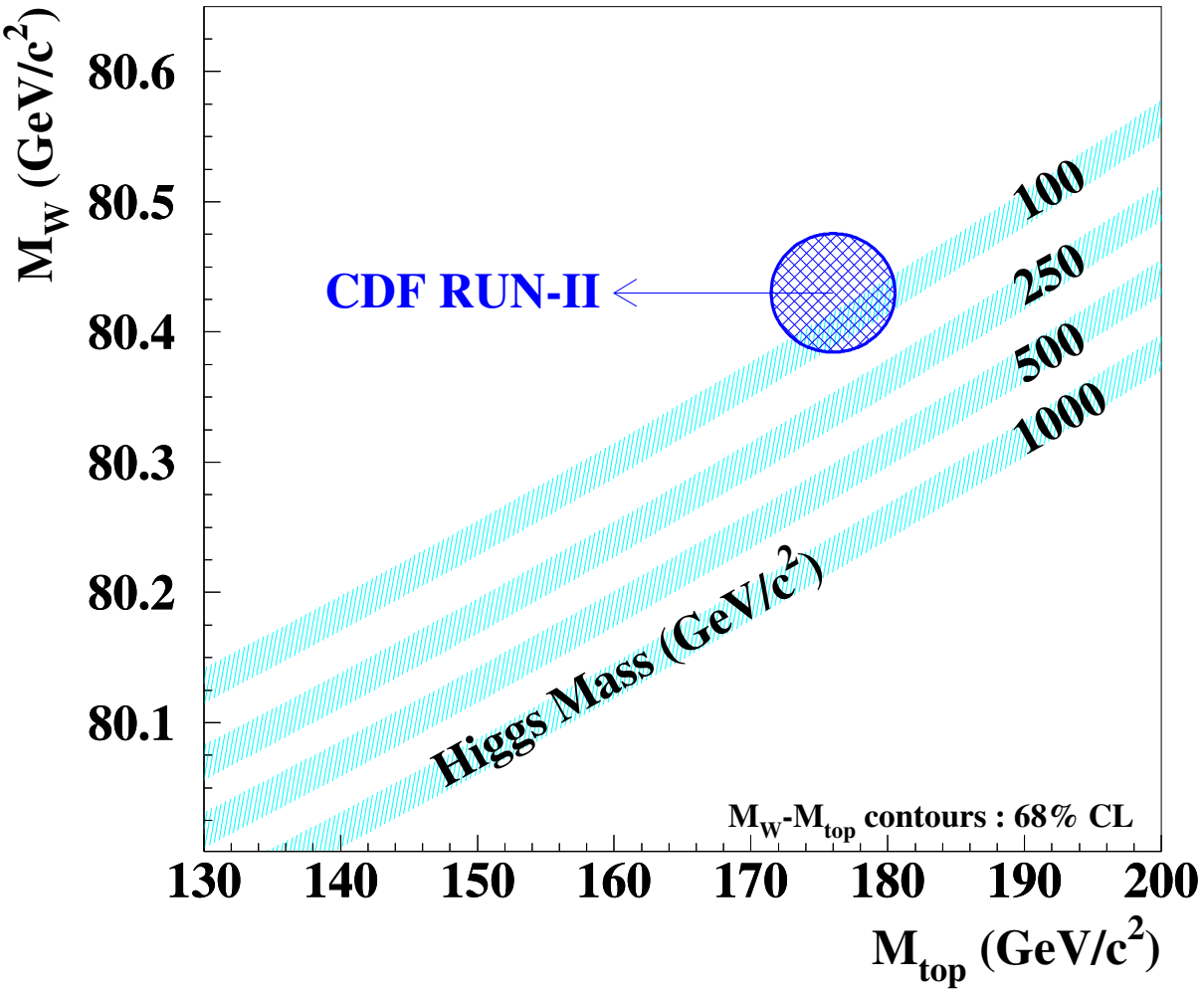
Measure angular correlations and decay kinematics

- Polarization of W^+ will be measurable
- Spin correlations (expect 90%) also detectable

Single top production

- Measure σ_t with 10% uncertainty
- Measure V_{tb} with 12% uncertainty

Expected Run IIa Result



Summary

Debut of top using Run I data coming to close

- Have seen that it looks much like a SM fermion
- But top mass scale is enigmatic

All this sets the stage for Run II

- Run for 2-4 years, with goal of $\sim 2 - 15$ fb^{-1}
  - $\Rightarrow$ Increase top quark sample $\times 50$

By the time next generation collider turns on,

- Top will be pretty well-studied
  - Reveal some property that points toward a more complete theory?
  - Will at least be an important background
- Will be able to reconstruct millions at the LHC!
  - It will become the "high-statistics" probe of the next energy scale