The Debut of the Top Quark

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Overview

- Boring Standard Model Stuff
- What Does Dancing with the Top Quark Tell Us
- Producing and Detecting Top
- Sizing up the Top Quark
- On to Run II

Work done in collaboration with Pierre Savard and Andrew Robinson

UBC Colloquium, 18 May 1999

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. $\delta_{M_z}/M_z \sim 8 \times 10^{-5}$)

It predicted existence of top quark almost 20 years ago

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

  - Production rate $\Rightarrow Q = -1/3$

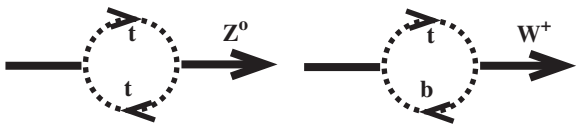
Studies established that it should have a partner

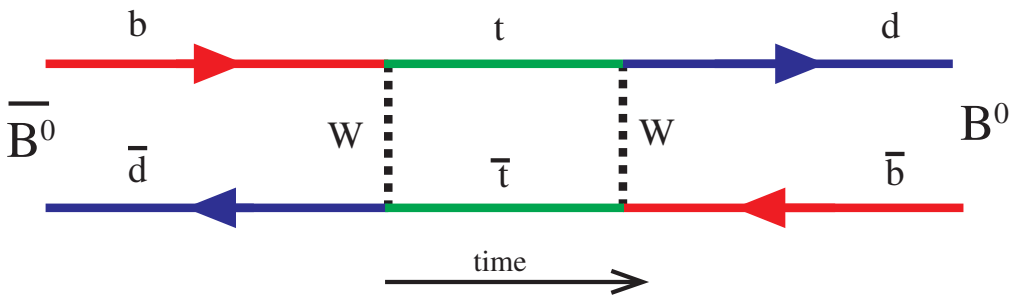
- Certain types of decays didn't occur
  - decays like $b \to \mu^+\mu^- d$ not observed
- $e^+e^- \to b\bar{b}$ scattering suggested an $SU(2)$ state

The Top Quark Mass in the Standard Model

The SM "needs" a massive top quark

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





However, no real information on M_{top}

- In 1983, new it had to be large ($\gtrsim$ 20 GeV/c^2)
- Searches limited by this mass scale

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 doesn't have time to form
- T mesons $\sim$ degenerate (if there was 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 evidence in e^+e^- and $p\bar{p}$
  - Rate decreases sharply with M_{top}
  - By 1989, had set limit of $M_{top} > 77$ 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
  - Collider Detector at Fermilab (CDF)
  - DØ

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

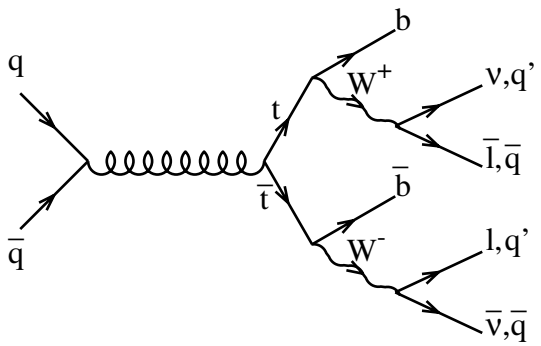
- April 1995, both collaborations announced discovery
- Confirmed SM predictions – $M_{top} \sim 170 - 190$ GeV/c^2
- Gave us a "free quark" system to study

  $\Rightarrow$ New frontier in particle physics

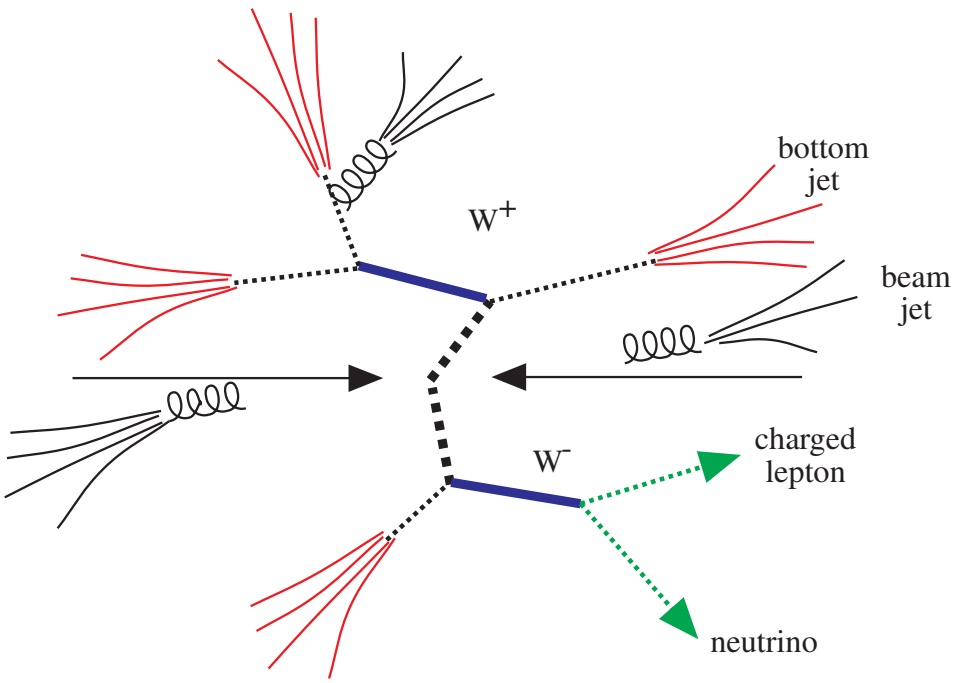
Reconstructing Top

Since top is pair-produced and β decays

- Expect to see 6 final state particles



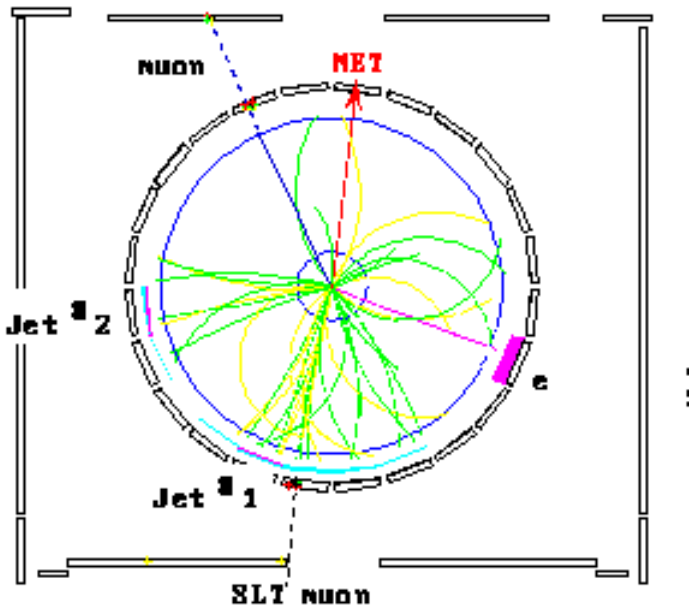
Life is normally not that easy – in reality:



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



Status of Collider Experiments

CDF and DØ collected ~ 100 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)

Various studies have strengthen initial 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)

Used these samples for top quark measurements

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

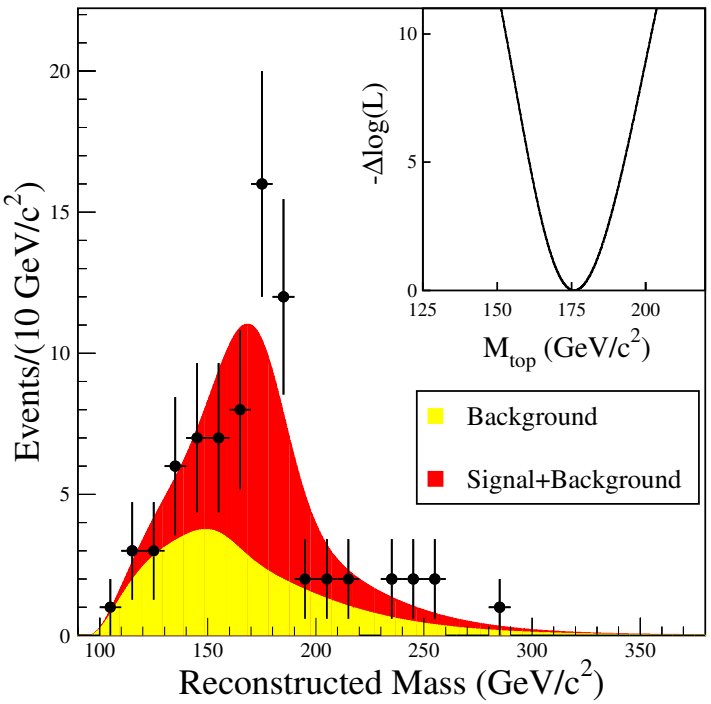
- Top Quark Decay Rates
  - Measured $t \to W^+b/t \to W^+q$
  - Searched for FCNC such as $t \to Z^\circ c$

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

Top Quark Mass

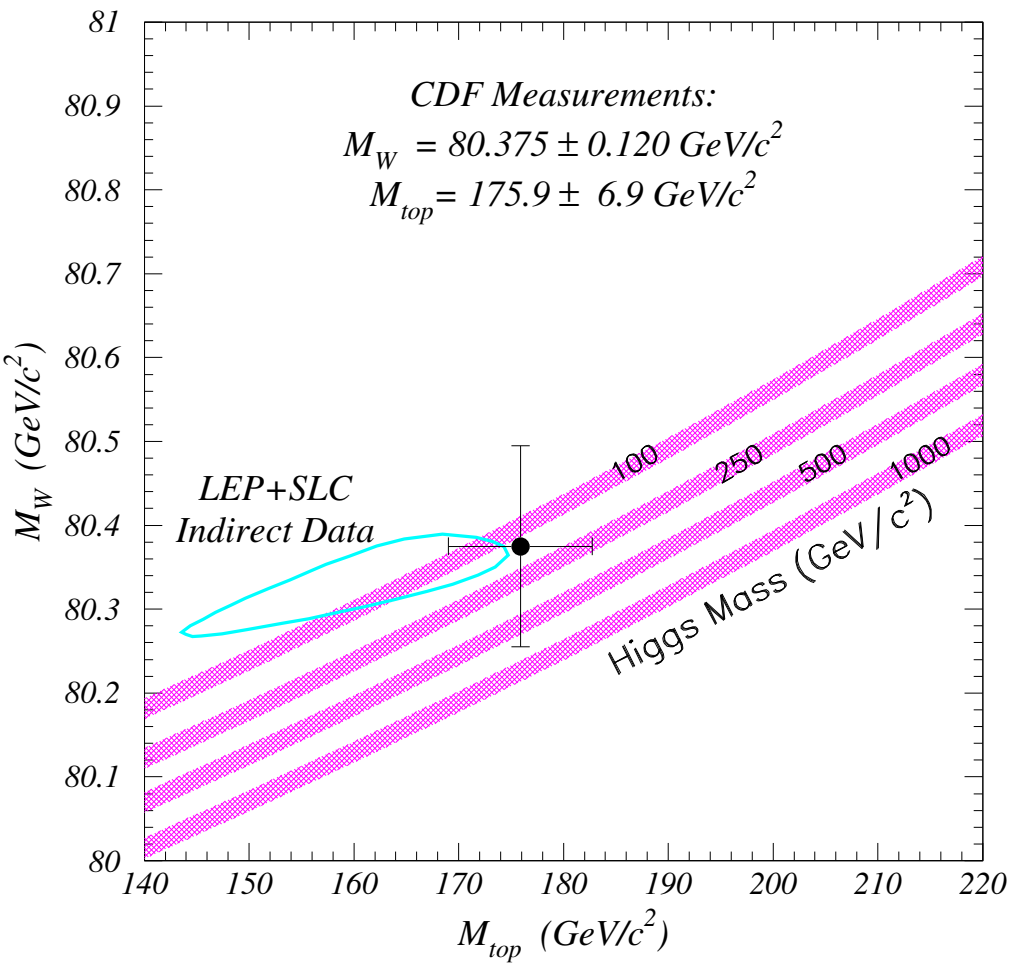
Measurements now limited by systematic uncertainties

- 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

$$M_{top} = 176.0 \pm 6.5 \text{ GeV c}^2 \text{ (CDF)}$$
$$M_{top} = 172.1 \pm 7.1 \text{ GeV c}^2 \text{ (DØ)}$$
$$M_{top} = 174.3 \pm 5.1 \text{ GeV c}^2 \text{ (RunI)}$$

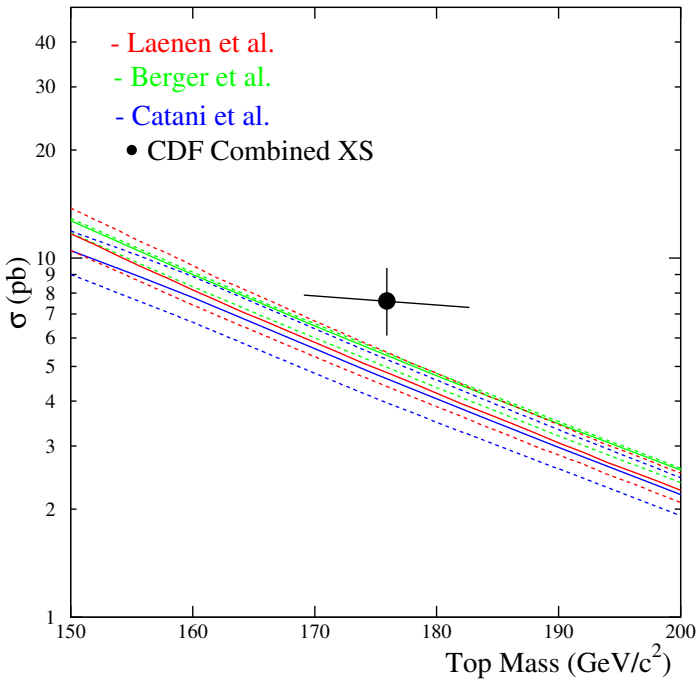

CDF Measurements:
M_W = 80.375 ± 0.120 GeV/c^2
M_{top} = 175.9 ± 6.9 GeV/c^2
LEP+SLC
Indirect Data
100
250
500
1000
Higgs Mass (GeV/c^2)
M_W (GeV/c^2)
M_{top} (GeV/c^2)
81
80.9
80.8
80.7
80.6
80.5
80.4
80.3
80.2
80.1
80
140
150
160
170
180
190
200
210
220

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

$$\sigma_{t\bar{t}} = 7.6^{+1.8}_{-1.5} \text{ pb}$$

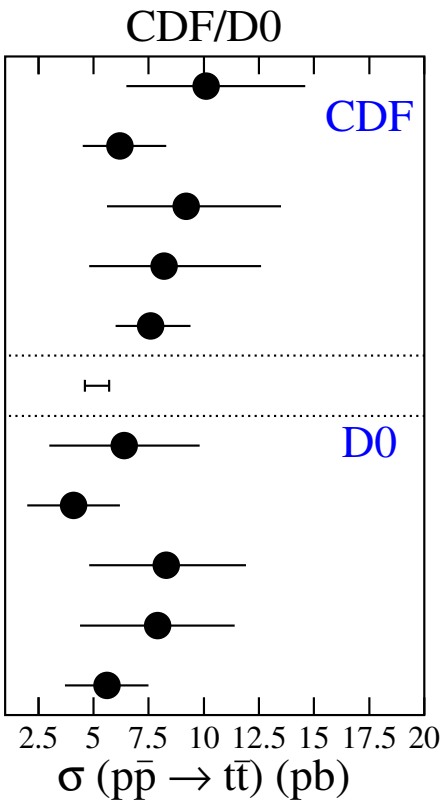


Rarest process ever measured in hadron collider!

- Theory predictions range from 4.7 to 5.5 pb

Comparison with DØ

Measurements by DØ also quite consistent

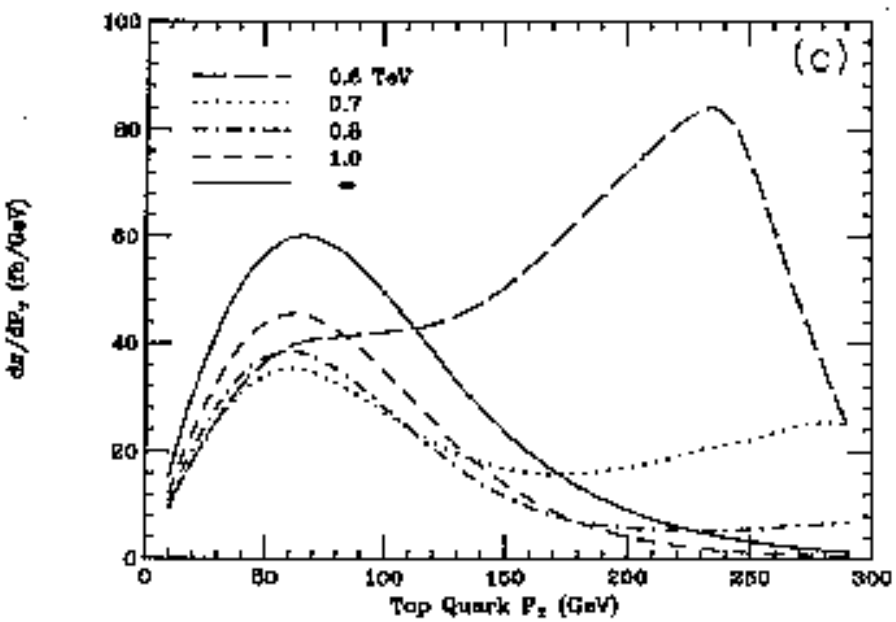


$10.1^{+4.5}_{-3.6}$ pb HAD
$6.2^{+2.1}_{-1.7}$ pb SVX
$9.2^{+4.3}_{-3.6}$ pb SLT
$8.2^{+4.4}_{-3.4}$ pb DIL
$7.6^{+1.8}_{-1.5}$ pb Combined
Theory (4.7 - 5.5)
$6.4^{+3.4}_{-3.4}$ pb DIL
$4.1^{+2.1}_{-2.1}$ pb L+J (topo)
$8.3^{+3.6}_{-3.6}$ pb L+J (tag)
$7.9^{+3.5}_{-3.5}$ pb L+J (had)
$5.6^{+1.8}_{-1.8}$ pb L+J (sum)

Top Quark Transverse Momentum Distribution

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 are a problem

- 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 the signal significance, require that

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

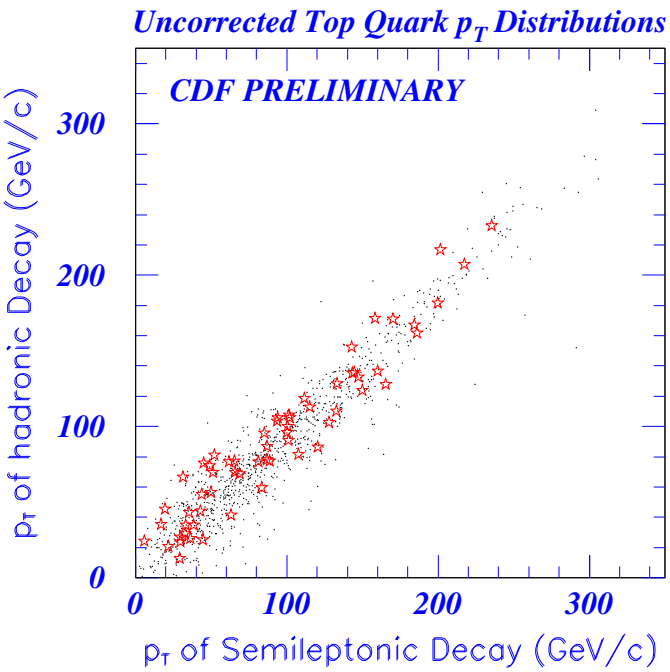
Kinematically fit event, constraining $M_{top} = 175$ GeV/c^2

- Require $\chi^2 < 10$

$\Rightarrow$ Left with 61 events

Measurement of P_T

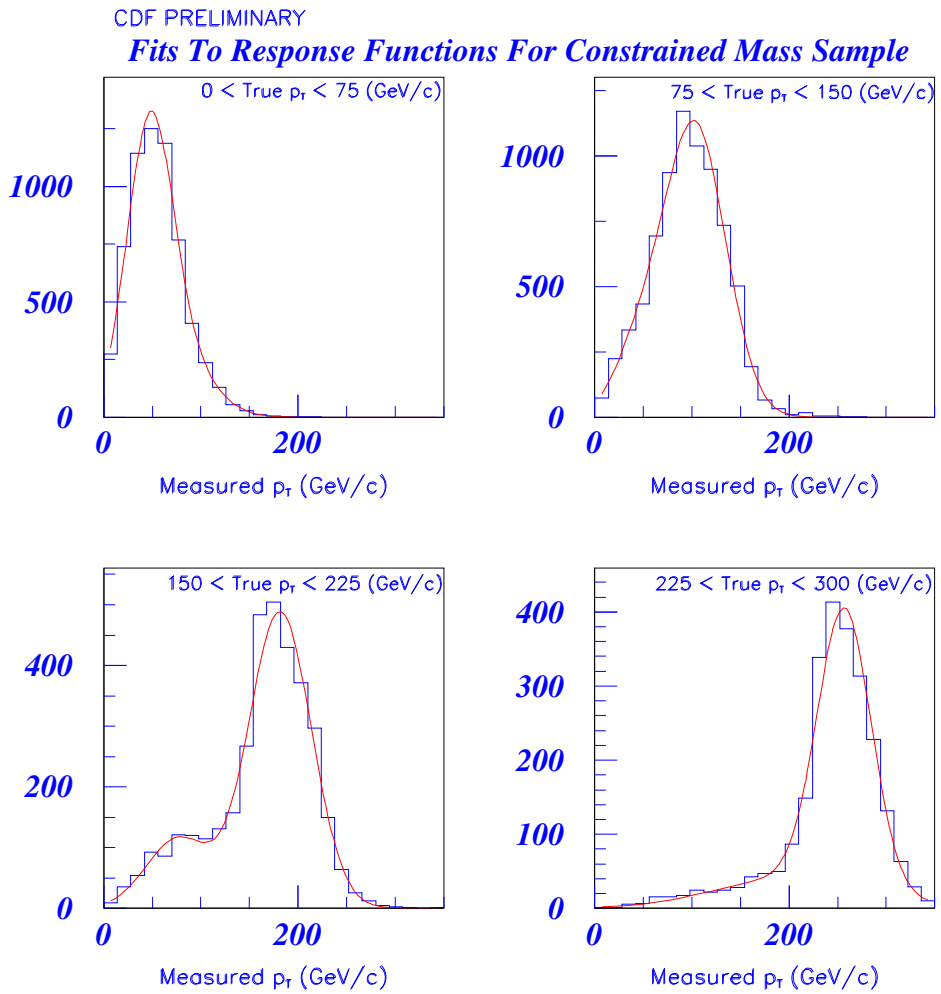
Measurements on lepton-side and jet-side are strongly correlated!



- Make measurement using only jet-side top quarks

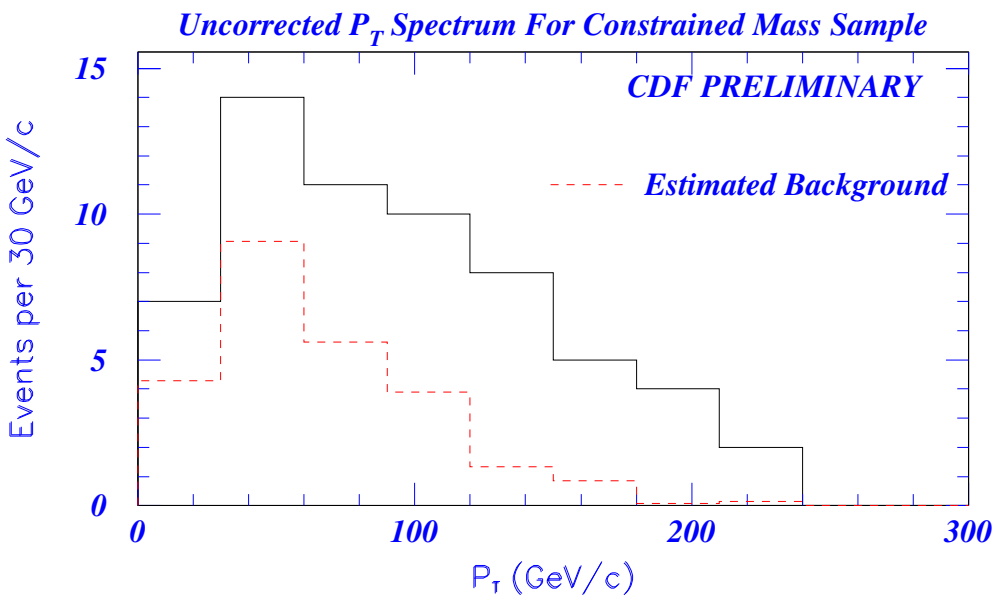
P_T Response Functions

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 $N_{bgd} = 24.6 \pm 5.8$ events

Resulting Fitted P_T Distribution

Perform unbinned likelihood fit to 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

$$\begin{aligned} R_1 &= 0.29^{+0.18}_{-0.18} \\ R_2 &= 0.42^{+0.18}_{-0.18} \\ R_3 &= 0.29^{+0.12}_{-0.10} \\ R_4 &= 0.000^{+0.035}_{-0.000} \end{aligned}$$

Confidence Level Interval on R_4

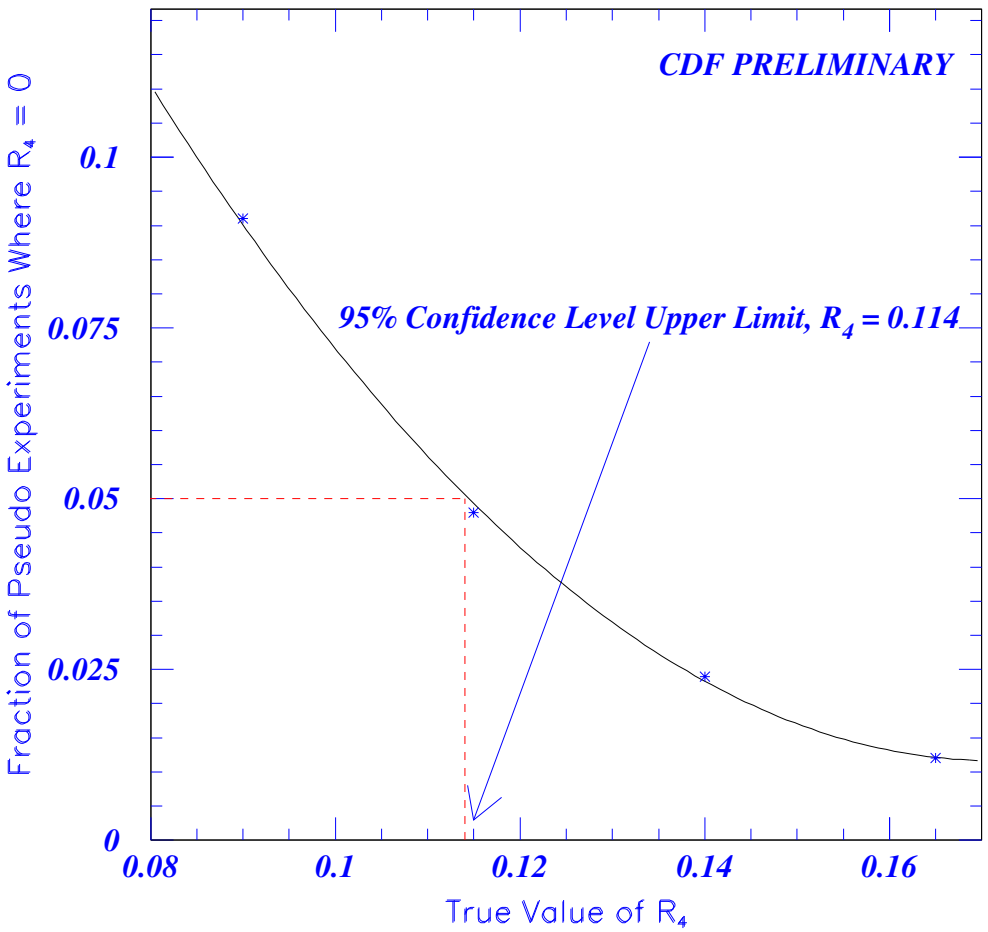
Obtain $R_4^{\text{fit}} = 0$ (fraction of top with $P_T > 225$ GeV/c)

- Use non-Bayesian technique to determine what we can infer about "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 pseudo experiments 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

- Without systematics, $R_4 < 0.109$ at 95% CL

Magnitude of Various Systematics

Have used combination of MC and data to estimate systematic uncertainties

- Largest relates to how well we "unfold" data
- But dominated by statistical uncertainties

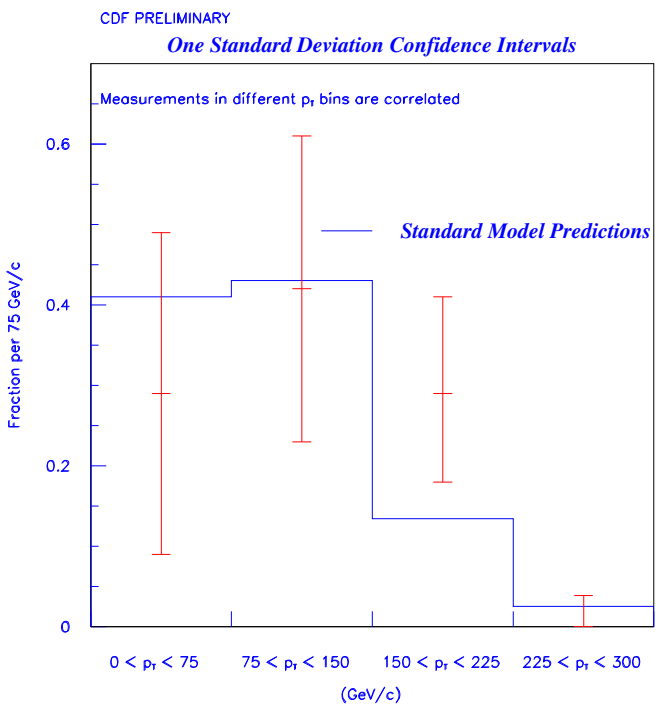
CDF PRELIMINARY

Syst.	δR_1	δR_2	δR_3	δR_4	$\delta(R_1+R_2)$
m_t	$^{+0.026}_{-0.000}$	$^{+0.00}_{-0.027}$	$^{+0.023}_{-0.000}$	$^{+0.000}_{-0.018}$	$^{+0.006}_{-0.012}$
ISR	± 0.016	± 0.011	± 0.005	± 0.005	± 0.007
FSR	± 0.038	± 0.023	± 0.010	± 0.005	± 0.015
JES	$^{+0.020}_{-0.028}$	$^{+0.037}_{-0.006}$	$^{+0.000}_{-0.008}$	$^{+0.000}_{-0.003}$	$^{+0.014}_{-0.000}$
Q^2	± 0.025	± 0.008	± 0.008	± 0.010	± 0.016
P_T	± 0.032	± 0.045	± 0.055	± 0.016	± 0.036
Acceptance	$^{+0.010}_{-0.023}$	$^{+0.013}_{-0.012}$	$^{+0.016}_{-0.014}$	$^{+0.000}_{-0.000}$	$^{+0.025}_{-0.011}$

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	$R_4 = 0.000^{+0.035}_{-0.000}(\text{stat})^{+0.019}_{-0.000}(\text{syst})$

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

- Will start data taking sometime in 2000 (April-Sep?)
- Run for 2-4 years, with goal of ~ 2 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