The Discovery of the Top Quark

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Overview

- Quarks and the Standard Model
- The Role of the Top Quark
- The Hunt
- The Discovery
- What We Know About Top Today
- Prognostications

Structure of Matter

Some "high school" science

- Matter is made up of atoms
- There are about 109 different species!
- Atom itself has structure:
  - consists of small hard "core" (nucleus)
    - nucleus made of protons and neutrons
  - large cloud of electrons
- We can describe all atoms using 3 particle types
  1. electrons (e^-)
  2. protons (p)
  3. neutrons (n)

But there are hundreds of particles like p and n's

- Hadrons (π, K, Δ, N*, ϕ, J/ψ, ...)
- Leptons (e^-, μ^-, τ^-, ν's)

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!

- Predicts 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

The Quark Picture

"Quarks R Us"

- Up-Up-Down $\leftrightarrow$ proton
- Up-Down-Down $\leftrightarrow$ neutron

Heavier quarks are unstable

- Decay by emitting a W^+ or W^- boson

$$c \to W^+ s$$

$$b \to W^- c$$

- Lifetimes are $\tau \sim 10^{-12}$ s

All sorts of questions:

- Why are there so many flavours of quarks?
- Why do they have their unique properties?
- What forces act on them?

Why a Top Quark?

In 1977, Lederman et al. discovered a new particle

- 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

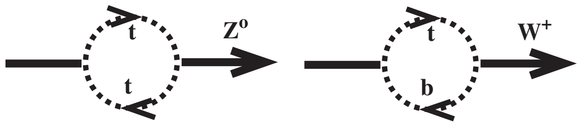
$\Rightarrow$ A sixth quark, known as "top" or "truth"

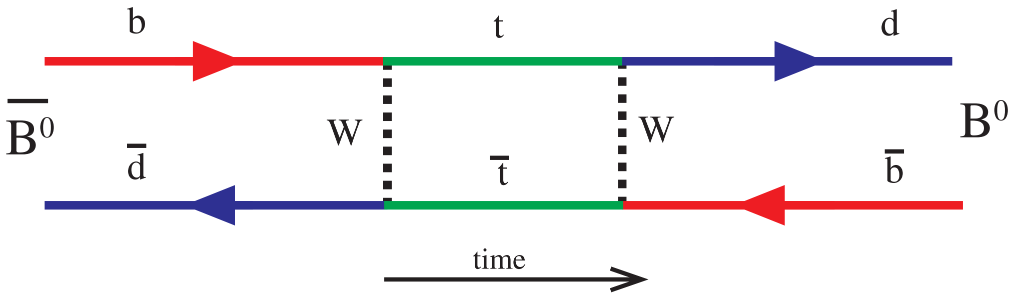
- Would have $Q = +2/3$

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
  - $b - \bar{b}$ 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

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

- 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

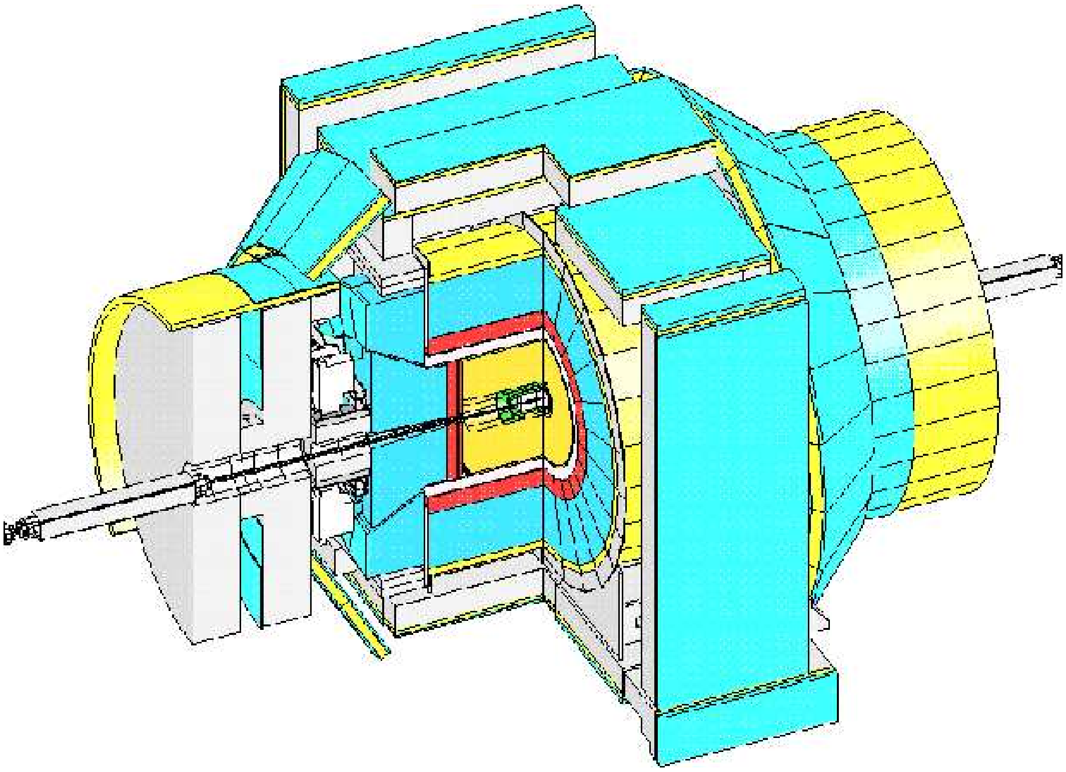
By 1992, had new measurements of M_Z and M_W

- 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)

The CDF Detector

Designed to record high-energy $\overline{p}\,p$ collisions

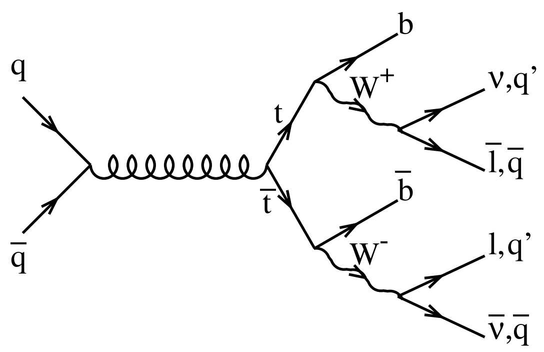
- A 5000-ton cylindrical device
- Can create an "image" of the collision
- Originally built in 1982-86
- Seen it's third (and final?) upgrade



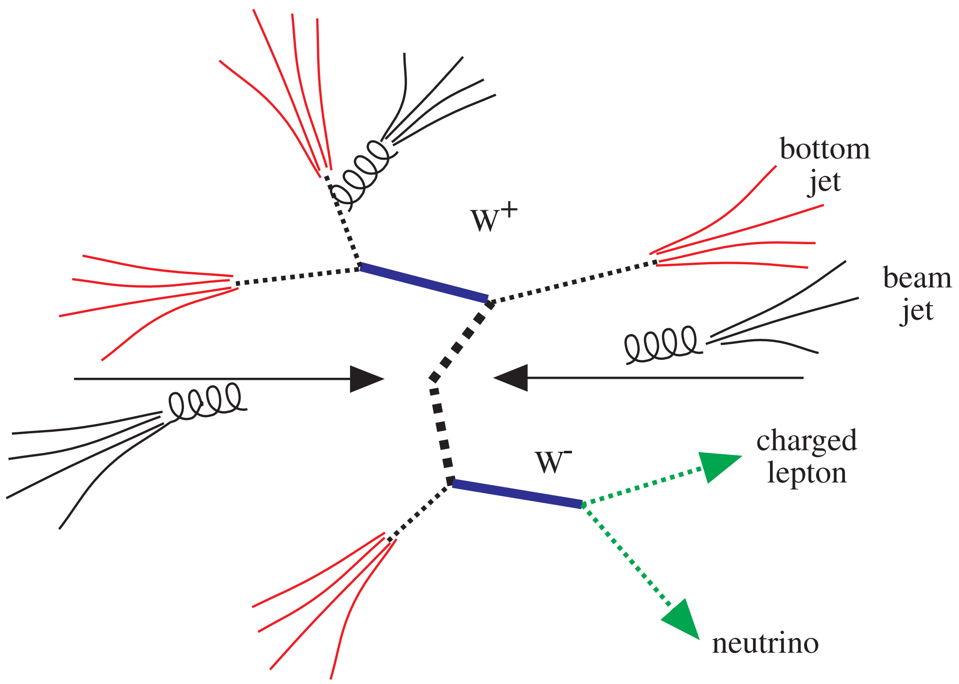
Reconstructing Top

Since top is pair-produced and β decays

- Expect to see 6 final state particles



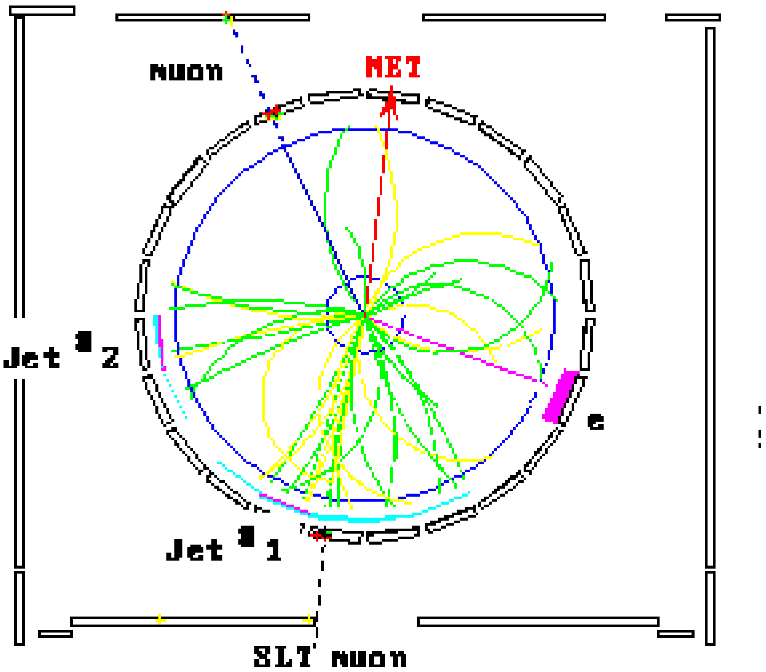
Life is normally not that easy – in reality:



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

In order to identify top candidates

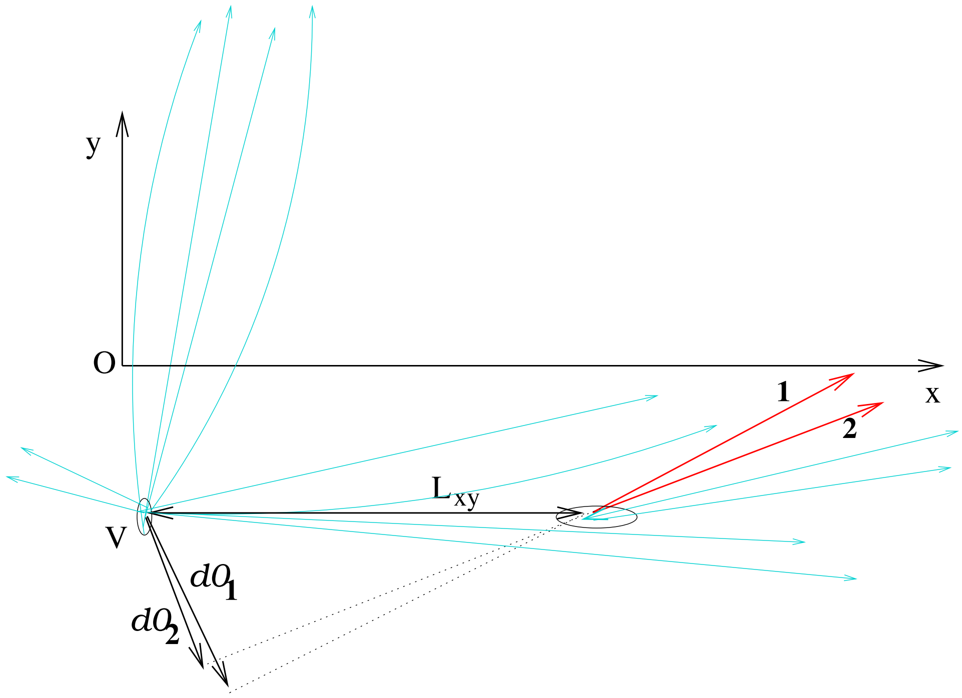
- Only 1 collision in $\sim 10^{10}$ expected to produce a top quark
- Search for $W \rightarrow l\nu_l$ candidate
  - Electron or muon with $P_T > 20$ GeV/c
  - Missing transverse energy $\not{E}_T > 20$ GeV
- Search for at least one b jet
  - Most effective tool is to find a secondary vertex
- Some evidence of other W in event
  - Either two more jets or another lepton



Tagging B Quarks

Must be able to "see" b quarks when searching for top

- Secondary vertex tagging primary technique (SECVTX)
  - Identify tracks with large impact parameter
  - Search for 2 or 3-track combinations with large L_{xy}



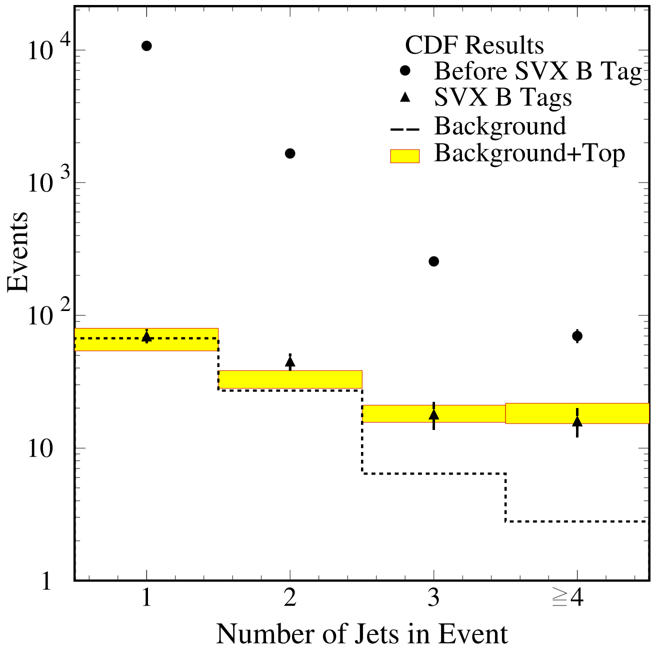
- Can tag $\sim$ 40% of top quark events

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



Discovery of Top

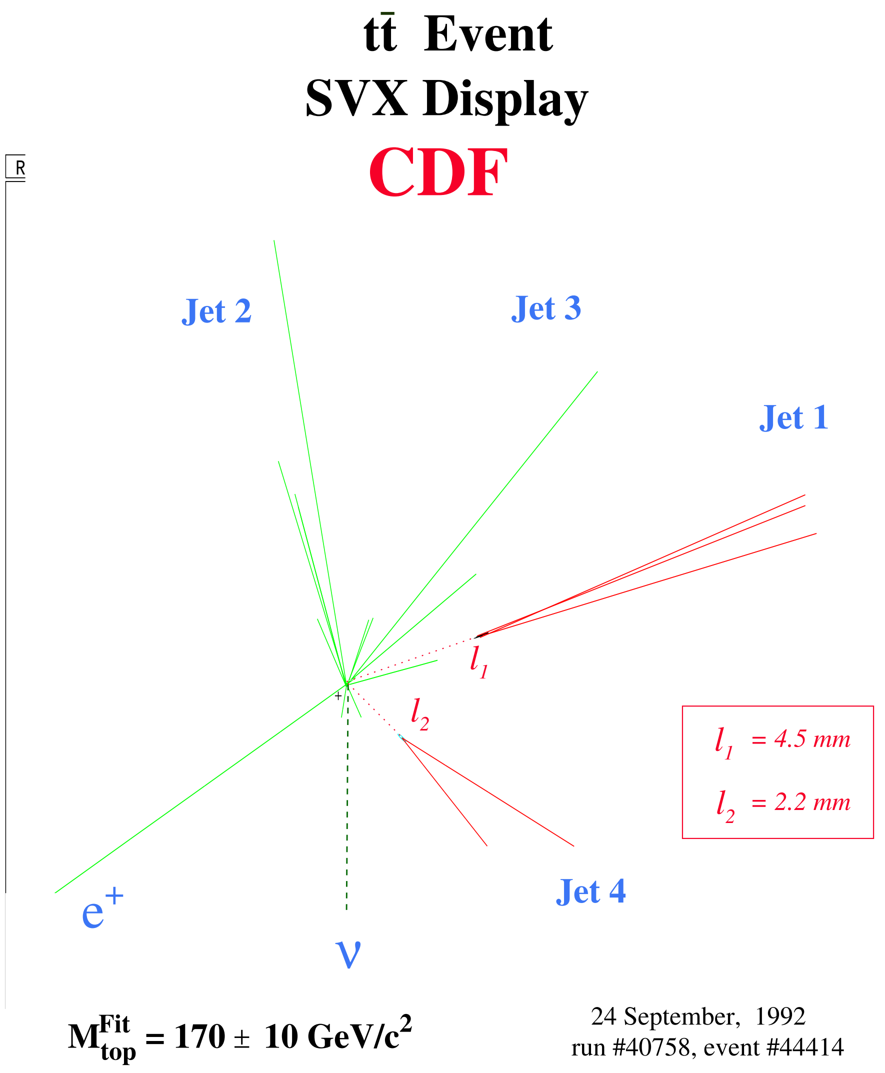
Hints of top production appeared as early as 1993

- 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
  - Decays before combining with other quarks
  - No complications associated with QCD force

Convincing "Smoking Gun" Events



Status of Collider Experiments

CDF and DØ collected $\sim 110\ \text{pb}^{-1}$ 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?

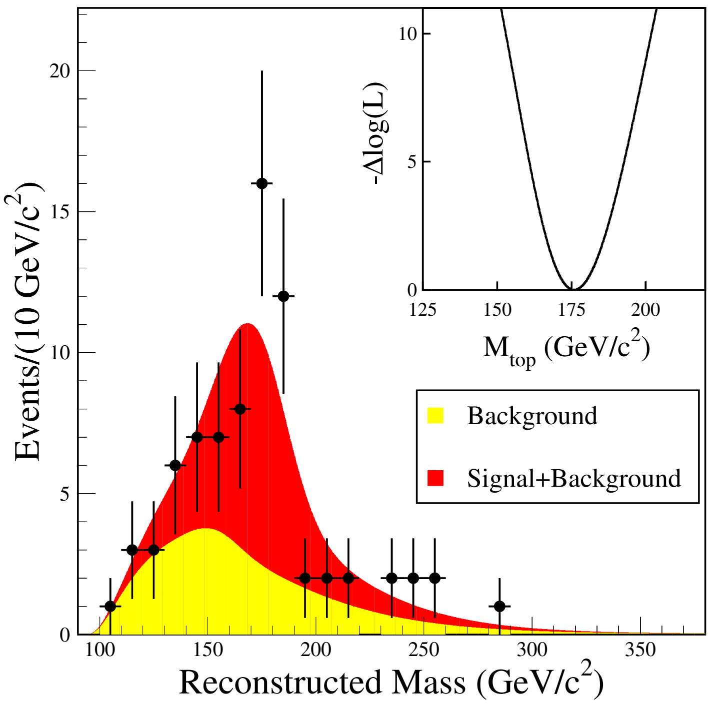
- Top Quark Mass
  - SM constrains it to M_W/M_Z
  - Important consistency check of theory
- Top Quark Production Cross Section
  - Predicted by QCD with less uncertainties than σ_b
  - Look for single top production
- Top Quark Decay Rates
  - Measured $t \to W^+b/t \to W^+q$
  - Look for $t \to H^+b$
- 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

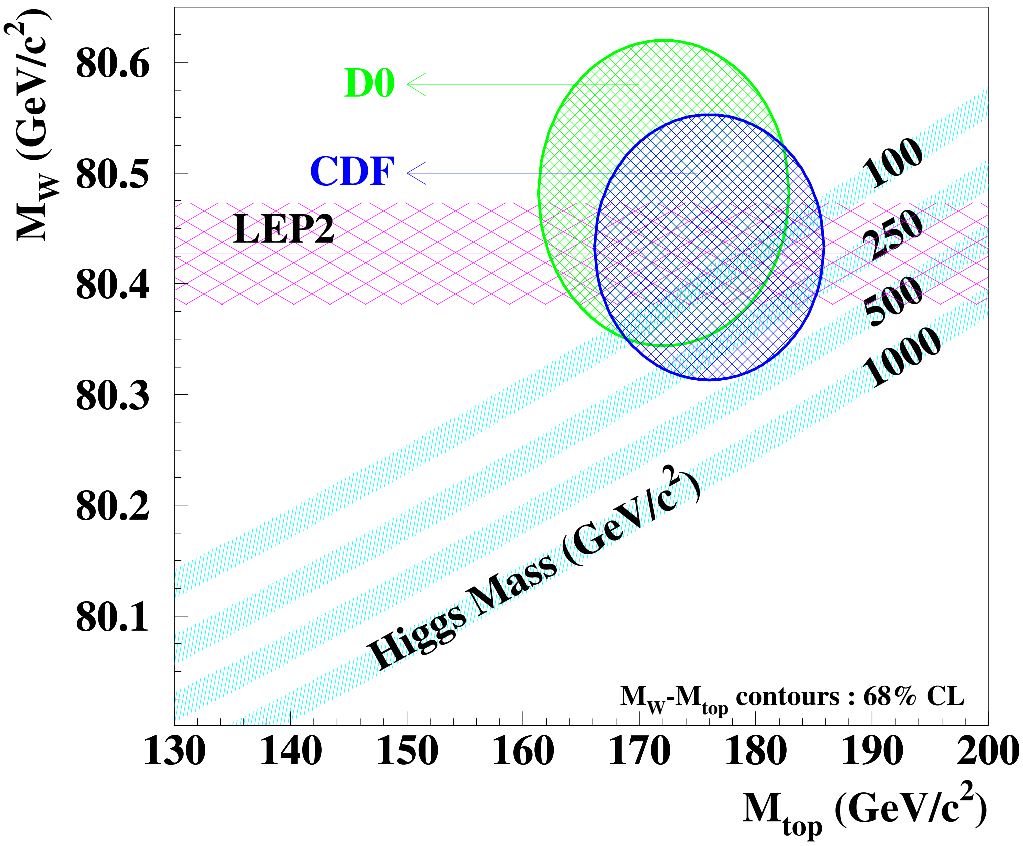


The final Run I values are

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

Latest W boson mass results

$$M_W = 80.433 \pm 0.079 \text{ GeV c}^2 \quad \text{CDF}$$
$$M_W = 80.482 \pm 0.091 \text{ GeV c}^2 \quad \text{D0}$$
$$M_W = 80.427 \pm 0.046 \text{ GeV c}^2 \quad \text{LEP2}$$

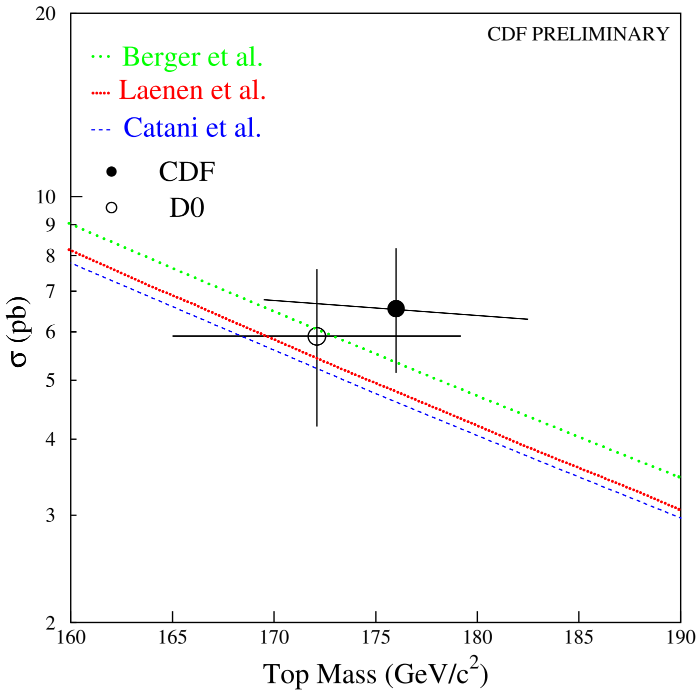


Top Quark Production Cross Section

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

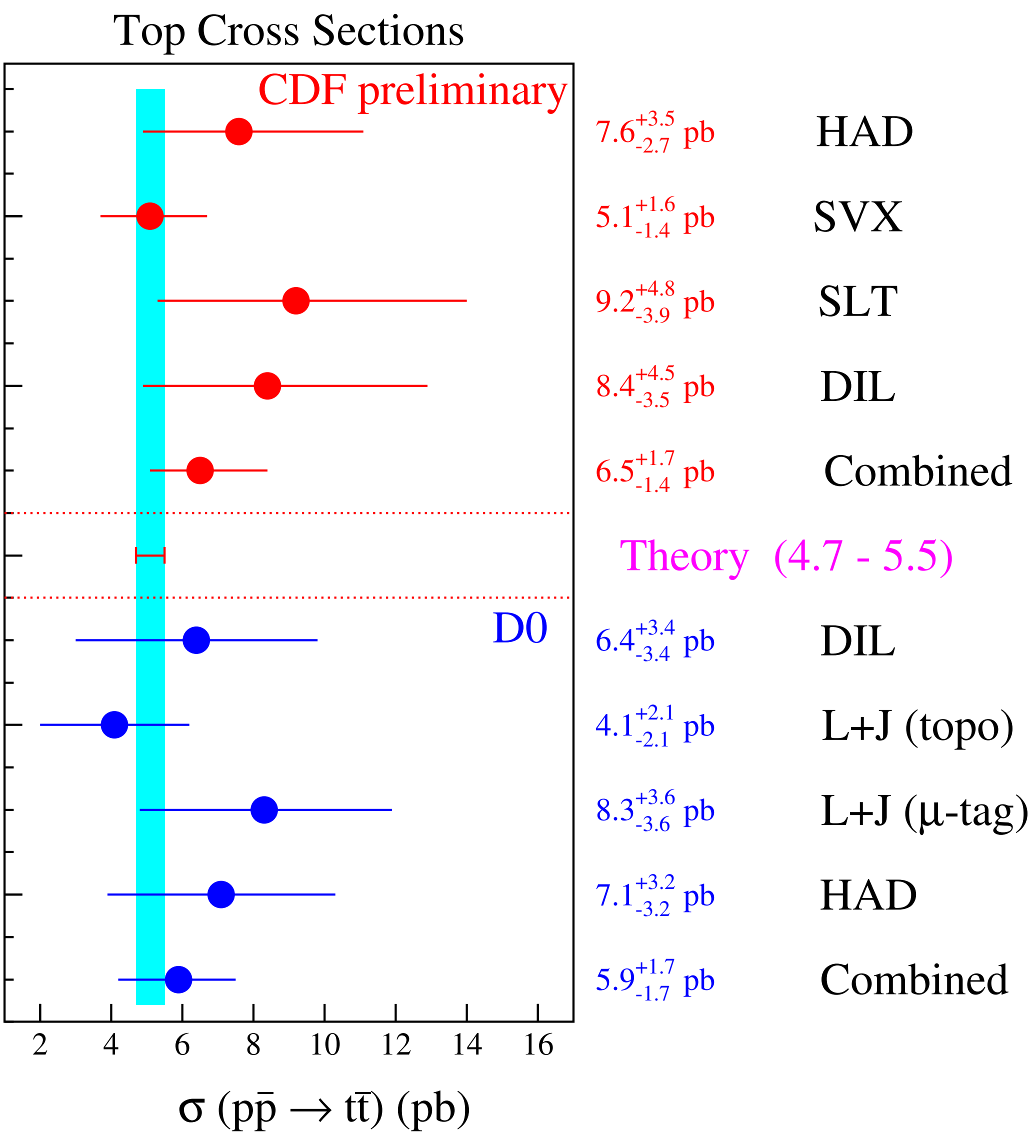
$$\sigma_{t\bar{t}} \;=\; 6.5^{+1.7}_{-1.4} \text{ pb}$$



- Theory predictions range from 4.7 to 5.5 pb

Comparison with DØ

Measurements by DØ also quite consistent



Run II Forecasts

Run II has started this spring at $\sqrt{s} = 2.0$ TeV

- CDF had an "engineering run" (partial SVX II) last fall
- Be taking physics data by July 2001

Will be worth the wait

- Begin with ~ 1 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
  - Begins to hint at the Higgs boson mass
  - Less than $\sim$ 210 GeV/c^2?

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

- Powerful "pointer" for Higgs searches

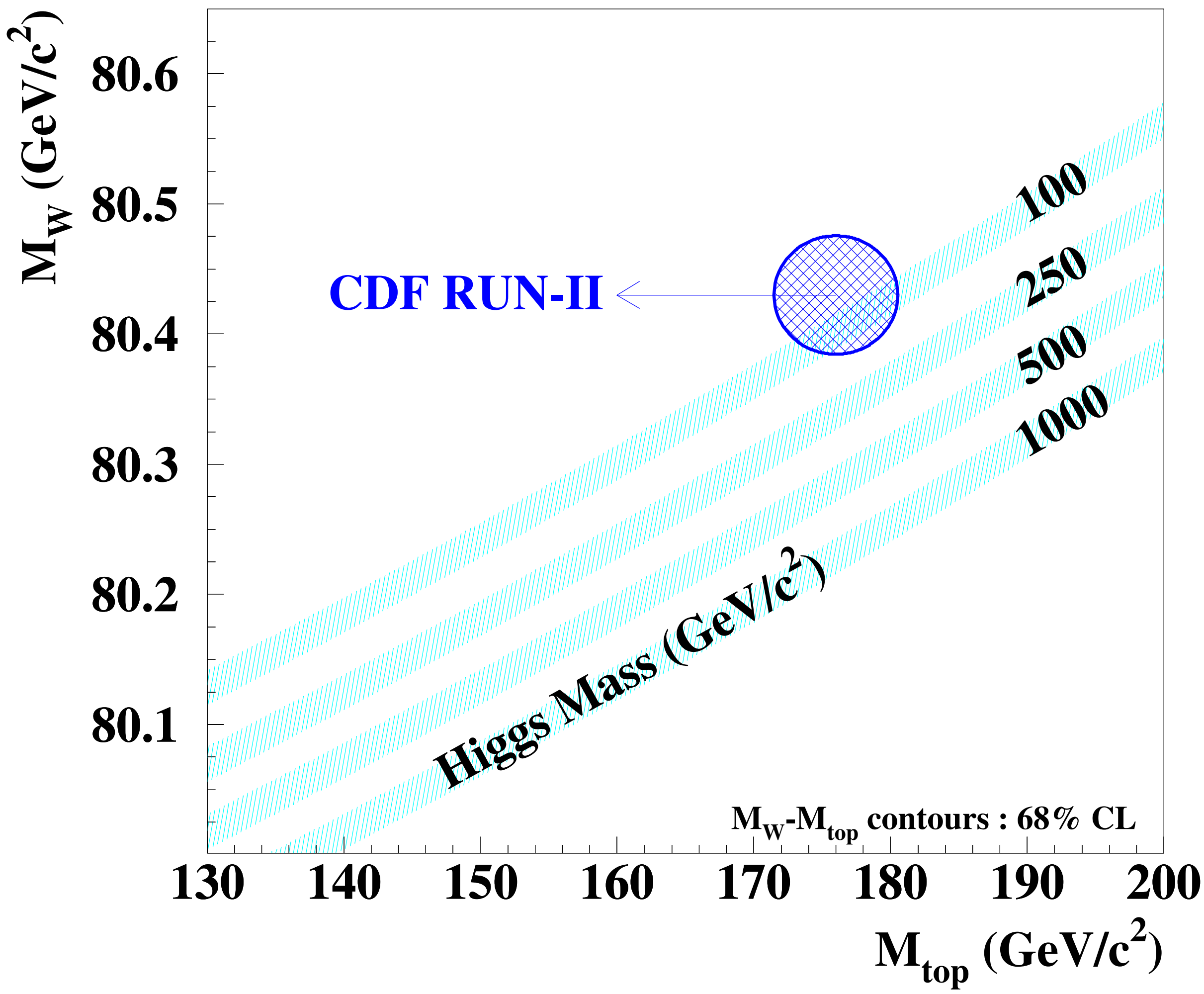
Measure angular correlations and decay kinematics

- Tell us about the electroweak force
- Polarization of W^+ will be measurable
- Spin correlations (expect 90%) also detectable

Single top production

- Measures the "width" of the top quark
- Measure σ_t with 10% uncertainty
- Measure V_{tb} with 12% uncertainty

Expected Run IIa Result



Summary

The debut of top is 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 next set of experiments

- 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