The Search for Top

1. The Current Paradigm—The Standard Model
2. How We "Discover" Quarks
3. Why Must the Top Quark Exist
4. Search for Top at CDF
5. What to Look for in the Future

$\boxed{\text{Standard Model of Elementary Particles}}$

Particle physics before ~ 1960 had established

- Elementary particles appeared to be the basic constituents of universe

  electron ($e^{\pm}$)
  proton (p)
  neutron (n)

- Four fundamental interactions or forces:
  1. **Strong Force**—bound nucleons (p, n) together
  2. **Electromagnetism**—bound e^{-} to nuclei
  3. **Weak Force**—responsible for neutron β decay
  4. **Gravity**—most obvious, but also the weakest

- Host of other "elementary particles"
  - neutrinos (ν_e, ν_μ) ("...who ordered that?")
  - muon (μ)
  - lots of other hadrons (π°, $K^{\pm}$, Δ's,...)

  Seemed to be spare wheels....

Over the last 3 decades, pieces have come together:

- Hadrons are composite objects made up of quarks

- 3 "generations" of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

- Three of the four forces can be described by relativistic quantum field theories:
  - "bosons" mediate each force

EM	γ
Weak	W^+, W^-, Z°
Strong	$gluons$

Evidence for Quarks

First solid evidence for proton structure came from SLAC

- high energy electrons were scattered off a H_2 target
- rate of scatters at very large angles quite high
- fits the "parton" model quite well

$\boxed{\textbf{What's Missing?}}$

This picture is enormously successful

- Describes detailed behaviour of W and Z bosons
- Accurate description of Electroweak force
- Apparently QCD also well described

There are two missing pieces

1. The Higgs particle
2. The Top Quark (the 6th quark—call it what you want)

Why the Higgs?

The **Higgs** is essential ingredient that allows the "unification" of the EM and Weak forces

- γ, $W^{\pm}$ and Z° are part of one "gauge" group
- γ mediates the EM force
  - massless, giving us inverse-square law force
- $W^{\pm}$ and Z° bosons mediate the weak force
  - masses come from interaction with a **Higgs** particle
  - gives uniquely "weak" nature to the force

The Higgs has not been found and could be quite heavy

- Searches for it exclude Higgs with mass < 60 GeV/c^2
- Rationale for next generation of accelerators

Why do We Need a Top Quark?

1. Behaviour of bottom quark implies it is a member of an SU(2) doublet

   - See this in scattering process

   $$e^+e^- \rightarrow b\bar{b}$$

   - Models with bottom as an SU(2) singlet predict flavour-changing neutral currents

2. EWK measurements imply existence of a "heavy" fermion that couples to W and Z bosons

$$\sin^2\theta_W \equiv 1 - \left(\frac{M_W}{M_Z}\right)^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu {M_W}^2}\left[\frac{1}{1-\Delta r(M_{top}, M_H)}\right] \quad (1)$$

where:

- M_W and M_Z are W and Z boson masses
- G_μ is μ decay constant
- Δr is "radiative" corrections

How Does One Find Quarks?

Quarks have unique properties

- come only in pairs ($q\overline{q}$) or triplets (qqq)
- QCD predicts that we cannot find a free quark
- come in three "colours"
- have different masses
  - $M_u \sim M_d \sim 150 - 200$ MeV/c^2
  - $M_s \sim 500$ MeV/c^2
  - $M_c \sim 1300$ MeV/c^2
  - $M_b \sim 5000$ MeV/c^2
- can decay via the EWK force

Existence of up, down and strange quarks inferred from

- baryon spectrscopy
- properties of elementary particles (n, p, π, ...)
- probes of interior of proton

Charm and bottom quarks took longer to discover

- greater masses required higher energy accelerators
- short lifetimes ($\tau \sim 10^{-12}$ seconds)

$\boxed{\text{Charm and Bottom}}$

Charm discovered in e^+e^- annihilations

- experiments at SLAC and BNL discovered J/ψ resonances
- consistent with $c\bar{c}$ bound states

Evidence also came from a study of the total e^+e^- cross section

$$R = \frac{\sigma(e^+e^- \to \text{anything})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Bottom discovered also as a bound state

- Υ resonances with mass of ~ 10 GeV/c^2

How Do We Find Top

The "best" way of producing top quarks is in proton-anitproton collisions

- high energy-collisions can produce heavy particles
- Can achieve high interaction rates

$$\mathcal{L} \sim 5 \times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Cross section for top production is fairly large

Searches for $e^+e^- \to t\bar{t}$ imply top must be heavy

- Require mass to top quark > 47 GeV/c^2
- Search limited by energy of collisions (~ 95 GeV)

Fermilab Tevatron collidor is highest energy $\overline{p}\,p$ collider

- 6 bunches of protons and 6 bunches of antiprotons
- Circulate in 6 km storage ring—6 interaction regions
- Two interaction regions are instrumented
  1. CDF detector
  2. D0 detector

$\Rightarrow \overline{p}\,p$ interaction rate of ~ 50 kHz

Tough part is that top quarks are produced rarely

- Many other processes also occur
- top quark is produced every 1 in 5×10^9 collisions

The CDF Experiment

Study of $\overline{p}p$ interactions at $\sqrt{s} = 1.8$ TeV

- 33 institutions
- 400+ physicists

The IPP Group consists of

	McGill University	**University of Toronto**
Faculty	Ken Ragan	Pekka Sinervo
RA	Kurt Biery Klaus Strahl	Andreas Hölscher
Grad Students	Yunling Ye Kostas Kordas Peter Musgrave	George Sganos Andreas Warburton Hyunsoo Kim Wendy Taylor

Experiment just completed data collection for Run IA

- Run IA (9/92 through 5/93) 22 pb^{-1}$\Rightarrow\sim$ 25 invpb
- Run IB (10/93 through 6/94) $\Rightarrow\sim$ 75 invpb

The CDF Detector

- general-purpose, 5000 ton detector

  Detector consists of:

  - Calorimeter to measure the energies of the particles
  - A magnetic spectrometer that measures charged particle momenta
  - A sophisticated real-time triggering system that records on average about 1 in every 50,000 collisions

Top Quark Search

CDF currently has proven capability for top search

- Current best preliminary limit is CDF dilepton analysis

$$\Rightarrow 40 < M_{top} < 108 \text{ GeV/c}^2 \qquad (95\% \text{ CL})$$

- Includes all decay channels with $e^{\pm}$'s and $\mu^{\pm}$'s

Lepton + Jets Channel is more sensitive decay mode

- lepton + neutrino ID eliminates QCD background
- Remaining background from $W +$ jets production
- Removed with B tagging
  - Secondary vertex tagging with SVX
  - Soft lepton tagging of B semileptonic decays

Data from current run is still being studied

- Currently reprocessing all data with new calibration
- Now beginning to see effects of radiation damage in SVX

$\boxed{\textbf{Dilepton Search}}$

Dilepton search requires two high-P_T isolated leptons

- Require $P_T > 20$ GeV/c for both charged leptons
- Remove Z° backgrounds in e^+e^- and $\mu^+\mu^-$ channels

Observe one new event with these cuts

- Preliminary background estimates
  - Physics backgrounds are small ($\simeq 0.5$ events)
    - $Z \rightarrow \tau\tau$, $b\bar{b}$ production
  - Fake backgrounds also appear to be $\lesssim 1$ event

To set limit

- Assume event arises from top production

- Include it with 1988-89 $e\mu$ candidate

  Exclude $28 < M_{top} < 108$ GeV/c^2 (95%CL)

$\boxed{\textbf{Lepton + Jets Search}}$

Select lepton + jet candidates by requiring

- Clean, isolated lepton candidate with $P_T > 20$ GeV/c
- $\not{E}_T > 25$ GeV to tag neutrino
- Require jets to have observed $E_T > 15$ GeV and $|\eta| < 2.0$
- Reject Z° and conversion backgrounds

Resulting sample is dominated by W +jets production

- Fake lepton backgrounds are < 10 %
- Most of the top signal would appear as 3 and 4 jet events

Reject background by requiring one jet to have a B tag

- Have studied 4 different SVX tagging algorithms
  1. JETVTX: Search for ≥ 2 tracks with large impact parameter that form secondary vertex
  2. BTDPHI: Search for ≥ 3 tracks that have correct ϕ-impact parameter correlations
  3. JPBTAG: Likelihood that all tracks in jet come from primary vertex
  4. Soft Lepton Tag: Search for lepton in jet from semileptonic B decay

Studied algorithms with "control" samples

- QCD jet sample (small inherent B content)
- Inclusive lepton samples (enriched B sample)
- $Z+$jet samples
- Tagged vertices on "wrong" side of primary

Summary of tagging studies

- Tagging efficiencies are ~ 0.3/event
- Tags from physics backgrounds small (~ 1 % of events)
  - Estimates from $W +$ charm probably most uncertain
- "Fake tag" form largest background
  - Estimated using QCD jets to be of order $\sim 5\%$ per jet
- Tagging performance uncertain for latter part of run
  - Reduction in tagging efficiency for last 1/3 of data run
  - $\Rightarrow$ assume 0.75 ± 0.25 tagging efficiency relative to MC predictions and studies with earlier data
  - Forms largest single systematic uncertainty

Define "signal sample" as events with ≥ 3 jets

- Tag three events (all three SVX algorithms tag these!)
- Estimate fake tag rate at $\lesssim 1$ event

Can compare observed tag rate with expectation for top production and backgrounds

- Cannot set any limit given small number of signal events

- Data does tend to favour a heavier top mass?

$\boxed{\textbf{Future Collider Runs and CDF Upgrades}}$

Fermilab Collider will begin Run IB in November 1993

- Run for ~ 12 months
- New LINAC injector
- Double maximum luminosity to 1.5×10^{31} cm^{-2}s^{-1}
- Goal is for CDF/D0 to collect ~ 75 pb^{-1}

CDF Upgrades for Run IB

- Replace downstream end of DAQ system
- SVX$'$ detector (complete replacement for SVX)
- Trigger improvements and L3 upgrade ($\times 2$)

$\boxed{\textbf{Conclusions}}$

- Search for Top Continues
- Standard Model top mass > 108 GeV/c^2
- Lepton + Jets analysis still inclusive
  $\rightarrow$ Wait for Run IB (75 pb^{-1}) for conclusion!