The Mysteries of the Top Quark

The Search for "Truth"

1. **How we Understand Matter**
2. **Building Blocks and the Glue**
3. **High Energy Collisions**
4. **Search for New Matter**
5. **Discovery of Truth**
6. **What Next?**

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7 March 2003

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The CAP

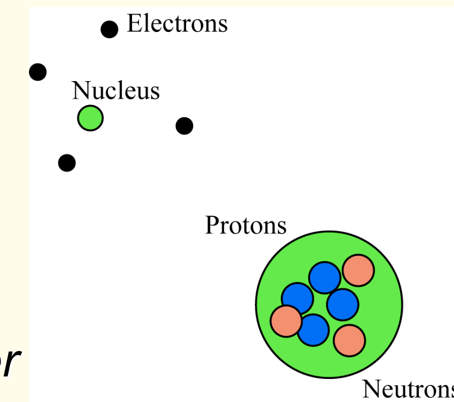
- **As Scientists,**
  - *We face the demands of a fast moving, technologically advanced society*
  - *We are concerned for the development and ultimate use of pure and applied science*
  - *The global community neccesitates our involvement in government, in industry, in education*

- **As Physicists,**
  - *We need to keep informed of the latest developments*
  - *We must be involved in opening our fascinating world to the youth of Canada*
  - *It is vital that we communicate with the public*
  - *It is essential that we have the ear of the government*

The CAP Fulfills this Role!

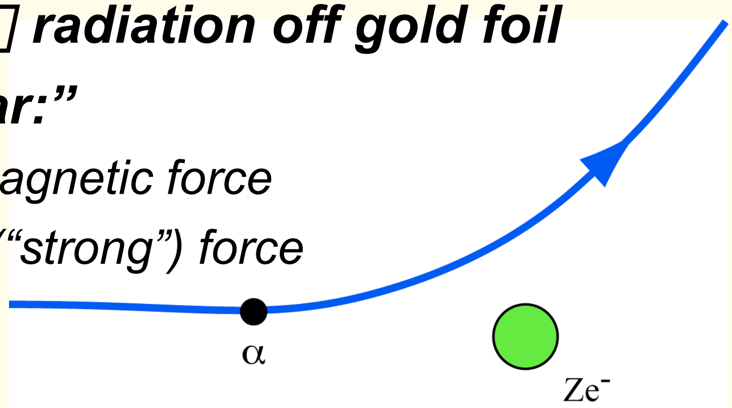
The Building Blocks of Our World

- **Go back to High School:**
  - ***Matter is made up of atoms***
    - – *Electron cloud*
    - – *Hard, small core*
      - *Protons*
      - *Neutrons*



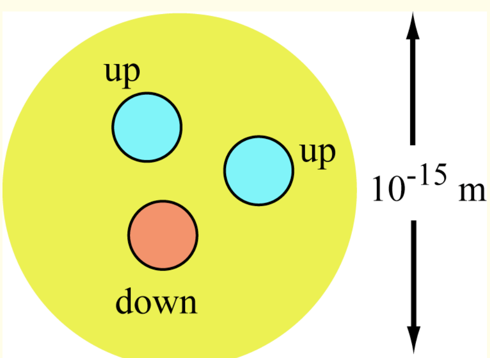
    - – *Can describe all matter*
      - *Just three types of building blocks*

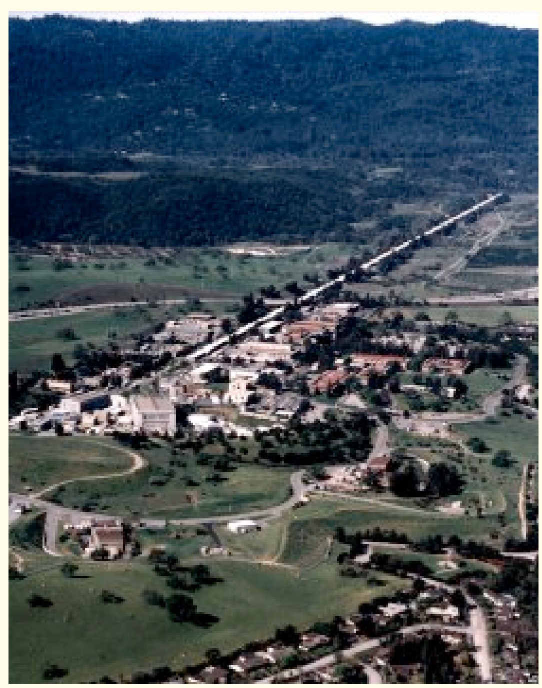
- **Discovered by Lord Rutherford**
  - ***Scattered □ radiation off gold foil***
  - ***The "mortar:"***
    - – *Electromagnetic force*
    - – *Nuclear ("strong") force*



Nucleons Deconstructed

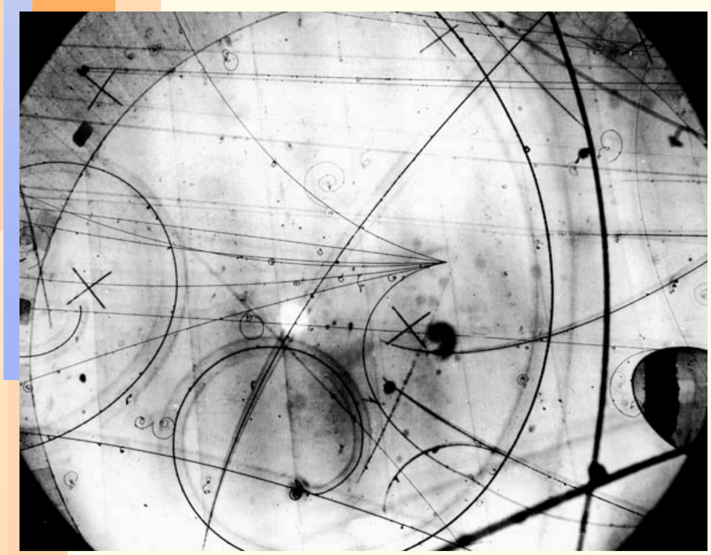
- ***Protons & neutrons have a size of about 10^{-15} m***
  - ***Use high-energy electrons to "see" into proton***
  - ***Studies at Stanford in early 1960's***
    - *3 objects inside proton*
    - *2 charge +2/3 - "up" quarks*
    - *1 charge -1/3 - "down" quarks*





1960 Quark Picture Gets More Complex

- **_High-energy collisions produced other "elementary particles"_**



Introduced "strange" quark
Decayed after about 10^{-6} s
Had a charge of -1/3

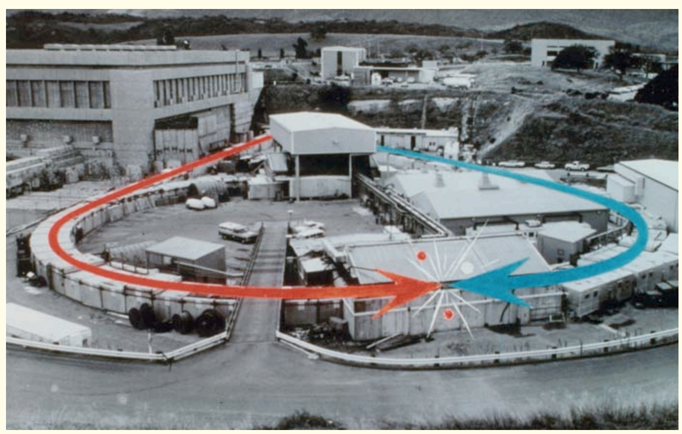
3 Quark Model: Explained over 100 elementary particles

- **_Led to new theory for "forces"_**
  - **_Mediated by force carriers_**
    - *EM force Photon*
    - *Strong force Gluon*
    - *Gravity Graviton*
    - *Weak force Intermediate Vector Boson*

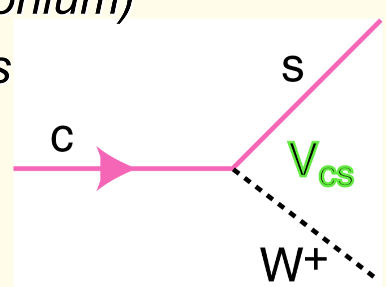
Discovery of Charm

- **Discovered another family of particles in 1974**
  - ***Had to introduce 4th quark - "charm"***
  - ***Mass of about 2 protons***
  - ***Lifetime of a few x 10^{-13} s***

SPEAR e^+e^- Storage Ring



- ***First observed as a quark-antiquark***
  - *Charmonium (a la positronium)*
  - *Lifetime implies it decays via the "weak" force*



Discovery of Beauty

- ***Lederman et al. discovered "mass bump"***
  - *Collided 400 GeV protons on nucleus*
  - *Produced events with □ pairs*
  - *Had to consist of quark-antiquark combination*

Christened:
"beauty"
or
"bottom"

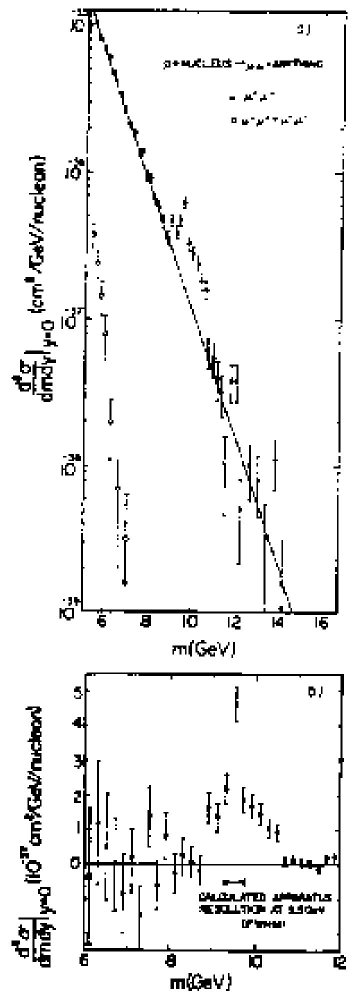
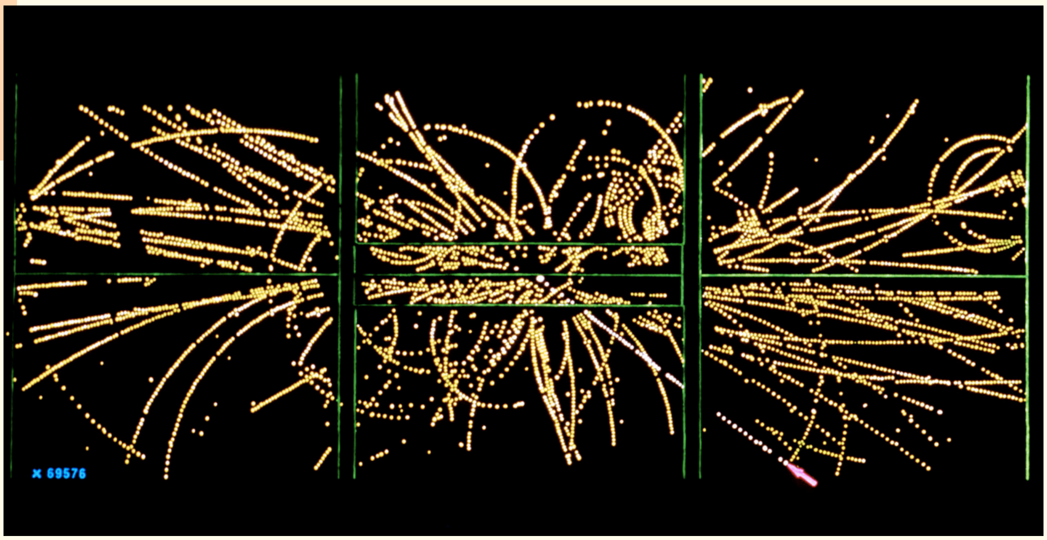


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign—dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

Theory Became the "Standard Model"

- ***Predicted 2 weak force carriers***
  - ***Observed in 1983 at CERN***
  - ***Great triumph for theory***



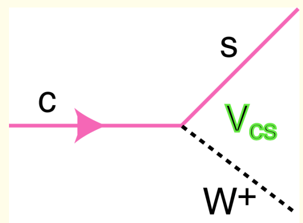
- ***Detailed studies in 1980's led to two predictions***
  - ***A 6th quark - "truth" or "top"***
  - ***Another particle - "Higgs" boson***

Why Should Truth Exist?

Standard Model picture:

- ***Quarks come in singlets or pairs, and interact via weak force***

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

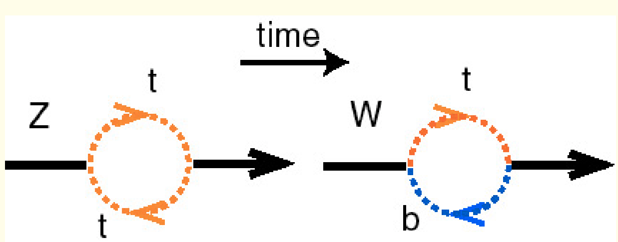


- ***Production of b quarks***

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

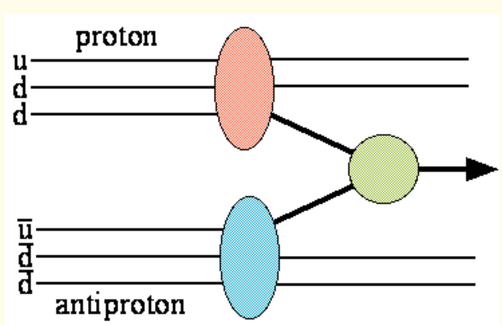
  - *Depends on # of partners to b quark*
  - *Showed that b quark behaved like a member of a "doublet"*
  - *By definition, partner was the t quark*

- ***New quark was heavy (> 20 GeV/c^2)***



Search for the Top Quark

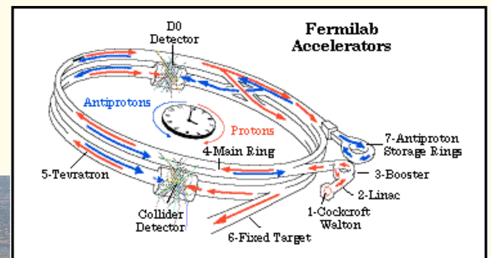
- **Began work in 1986 with about 450 other colleagues in CDF**
  - ***The problem:***
    - *Last time nature created top quarks was in first second of Big Bang*
    - *We had to recreate those conditions*
      - *Very high-energy collisions*
      - *Very dense environment*
  - ***The solution:***
    - *Collide protons and antiprotons at highest energies possible (1.8 TeV)*
    - *Record collisions & sift through the data*



Mimics
$T \sim 10^{15}$ K

Fermilab TeVatron Collider

- **6 km proton synchotron**
  - ***Accelerated protons to 0.9 TeV***
  - ***Ditto for anti-protons***
  - ***About 10^{11} protons/bunch***

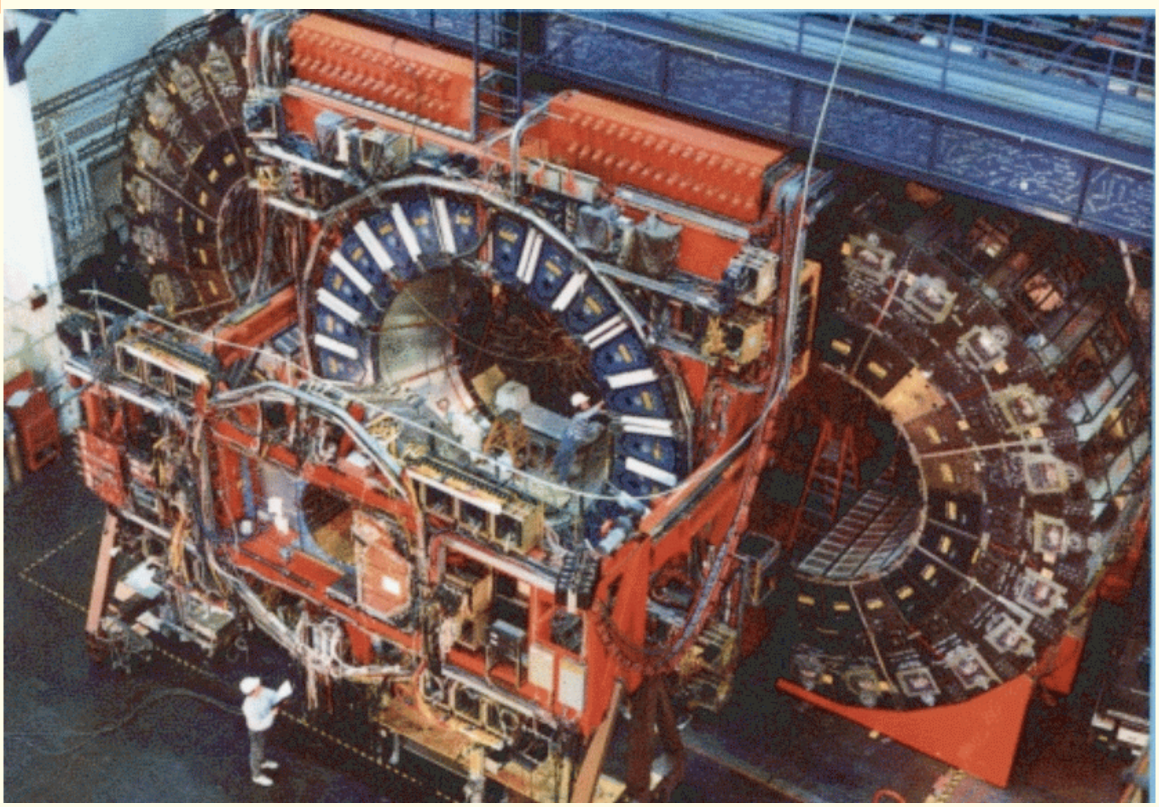


What To Do with the Collisions?

- **CDF collaboration designed and built instrument to record collisions**
  - ***Conceptually-***
    - *Want to see everything that results from matter-antimatter annihilation*
    - *Throw away uninteresting collisions*
    - *Piece together what initially took place*
  - ***Practically-***
    - *Particles are very energetic*
    - *Many particles (100's /collision)*
    - *Collision rates are very high*
      - *Million collisions per second*
      - *Each produces about 200 kBytes*
      - *Only about 1/100,000 "interesting"*

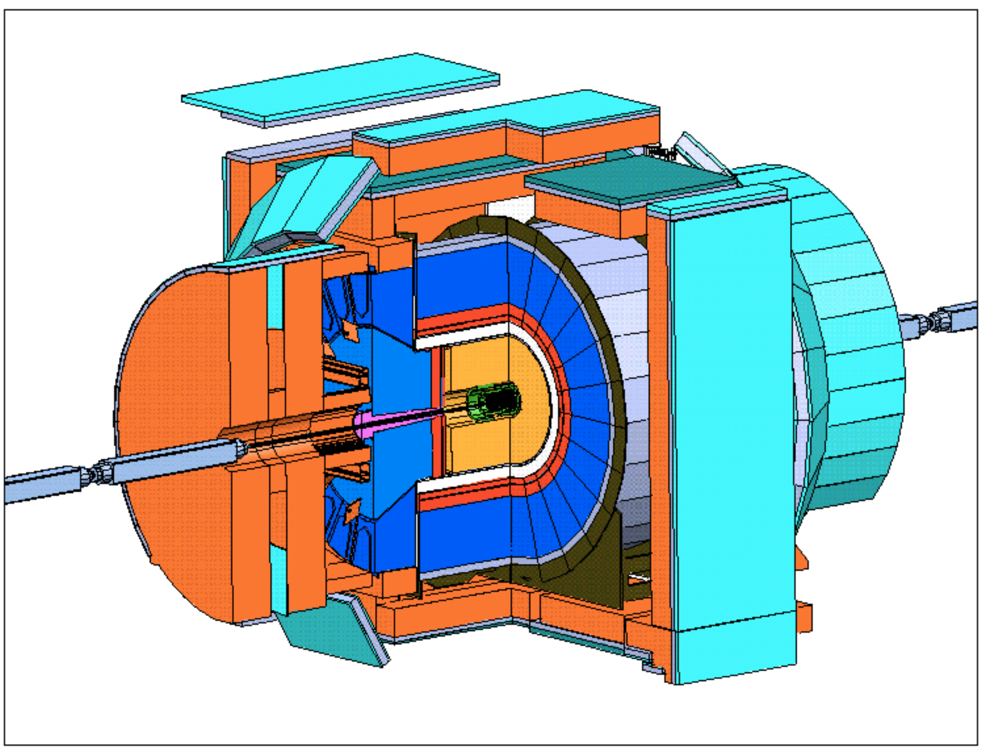
Collider Detector at Fermilab

- **_CDF is a US $250M instrument_**
  - **_Collaboration of about 450 people_**
  - **_Involves 40 institutions:_**
    - _US, Canada, Italy, Japan, Germany, Korea, Taiwan, Russia_



More on Detector

- ***Detector designed to***
  - ***"Image" products of a collision***
  - ***Record both charged and neutral particles***
  - ***Select about 1 in 100,000 collisions in real-time***

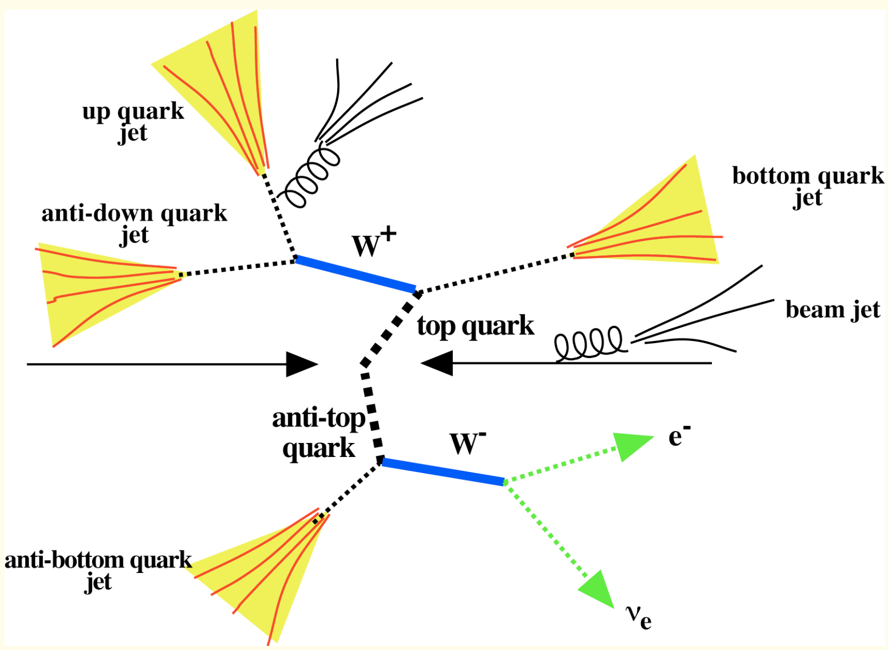


Canadian Team

- **Have a team of 14 people**
  - *4 professors, 2 postdocs*
  - *8 graduate students*
  - *Lots of technical resources*
- **Involved in designing, building and operating detector**
  - *Much of our effort involved in physics analysis of data*
  - *Need to develop advanced instrumentation*
  - *High performance computer systems at Toronto and Fermilab*

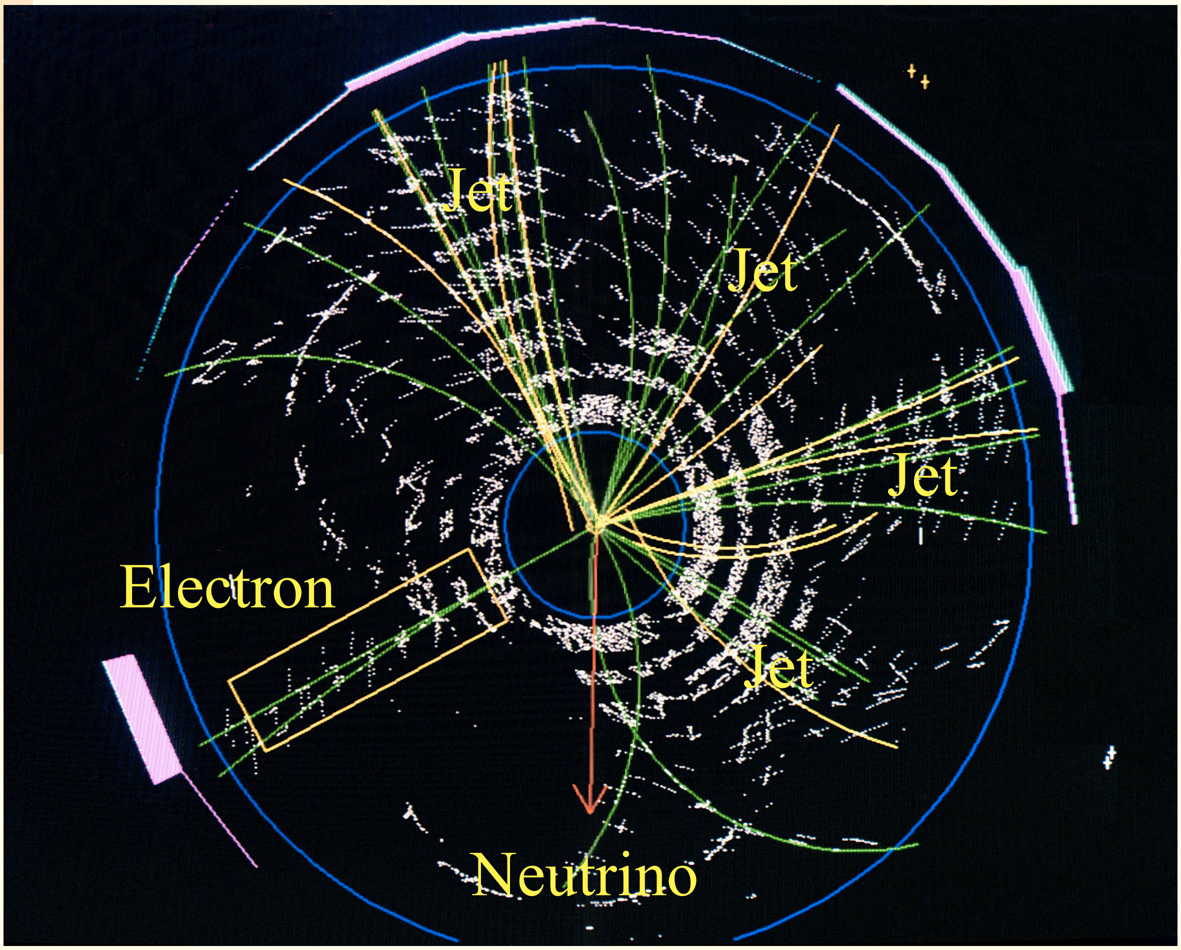
How Do We Find a Top Quark

- **Top quarks are pair-produced**
  - ***Come in matter-antimatter "pairs"***
  - ***Decay immediately into $W^{+}b$***



  - ***Results in very unusual signature***
    - *But very rare!*
      - *About 1 every 10 billion collisions*
      - *Can be easily fooled!*

Typical Event!

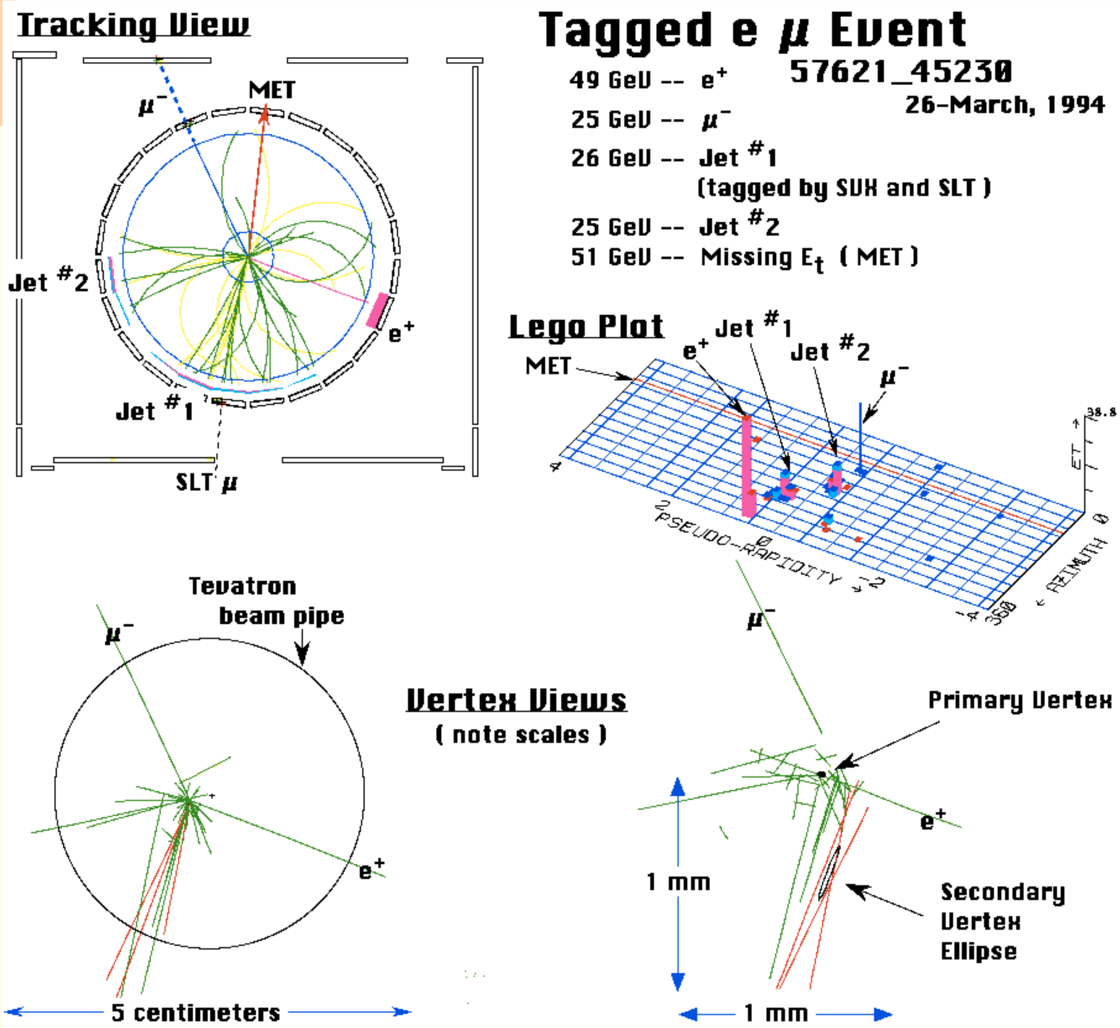


Of course, not so typical:

Require e and	*80,000 events*
Add 4 jets	*200 events*
Add "b tag"	*75 events*

The Data Mining Challenge

- **Collected data for 4 years**
  - *After 2 years, found in data*
    - 12 collisions out of a trillion
    - All very unique



What Did All this Mean?

- **Spent 3 months checking**
  - ***How many events could "mimic" the signal?***
    - *Concluded would see 5.6±0.6 events if top quark didn't exist*
    - *Chances of being fooled 1 in 300*
- **At that point, had to decide:**
  - ***Did we have a discovery?***
    - *Hint? A Suggestion? Hope? Vague speculation?*
  - ***Published a 61 pg PRD in Sep 1994***
    - *"Evidence for Top Quark Production…"*
  - ***But:***
    - *Other collaboration working at Tevatron (D0) couldn't confirm*
    - *We weren't convinced!*
    - *Continued to take data*

What Does Such a Paper Look Like?

PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

ARTICLES

Evidence for top quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

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And Don't Forget the Institutions….

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We present the results of a search for the top quark in 19.3 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. The data were collected at the Fermilab Tevatron collider using the Collider Detector at Fermilab (CDF). The search includes standard model $t\bar{t}$ decays to final states $ee\nu\bar{\nu}$, $e\mu\nu\bar{\nu}$, and $\mu\mu\nu\bar{\nu}$ as well as $e+\nu+$jets or $\mu+\nu+$jets. In the $(e,\mu)+\nu+$jets channel we search for b quarks from t decays via secondary vertex identification and via semileptonic decays of the b and cascade c quarks. In the dilepton final states we find two events with a background of $0.56^{+0.25}_{-0.13}$ events. In the $e,\mu+\nu+$jets channel with a b identified via a secondary vertex, we find six events with a background of 2.3 ± 0.3. With a b identified via a semileptonic decay, we find seven events with a background of 3.1 ± 0.3. The secondary vertex and semileptonic-decay samples have three events in common. The probability that the observed yield is consistent with the background is estimated to be 0.26%. The statistics are too limited to firmly establish the existence of the top quark; however, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. We present several cross-checks. Some support this hypothesis; others do not. Under the assumption that the excess yield over background is due to $t\bar{t}$, constrained fitting on a subset of the events yields a mass of $174\pm10^{+13}_{-12}$ GeV/c^2 for the top quark. The $t\bar{t}$ cross section, using this top quark mass to compute the acceptance, is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS number(s): 14.65.Ha, 13.85.Ni, 13.85.Qk

VELUT ARBOR ÆVO

Popular Press Had it's Say

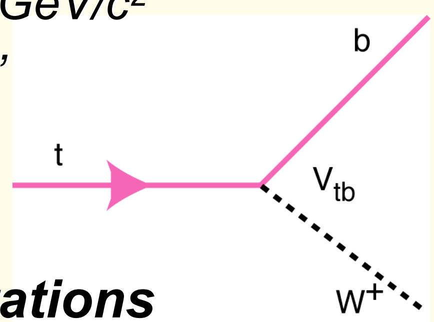
- **Newsweek (9 May 94)**
  - ***"How Many Scientists Does it Take to Screw in a Quark?"***

- **LA Times (10 May 1994)**
  - ***"Ask No More for Whom the Quark Quacks"***
- **Toronto Star (17 Jul 1994)**
  - ***"Memoirs of a Quark-Hunting Man"***

Next Steps in Search

- ***Continued to collect more data***
  - ***In year, had tripled the sample***
    - *Had 66 events, with 23 background*
    - *Chance of being fooled 1 in million*
  - ***Claimed a "Discovery"***
- ***Ended with 65 "gold" events***
  - ***Have now published over 25 papers on these 65 events!***
    - *Top quark mass 174±5 GeV/c²*
    - *Decays always "weakly"*

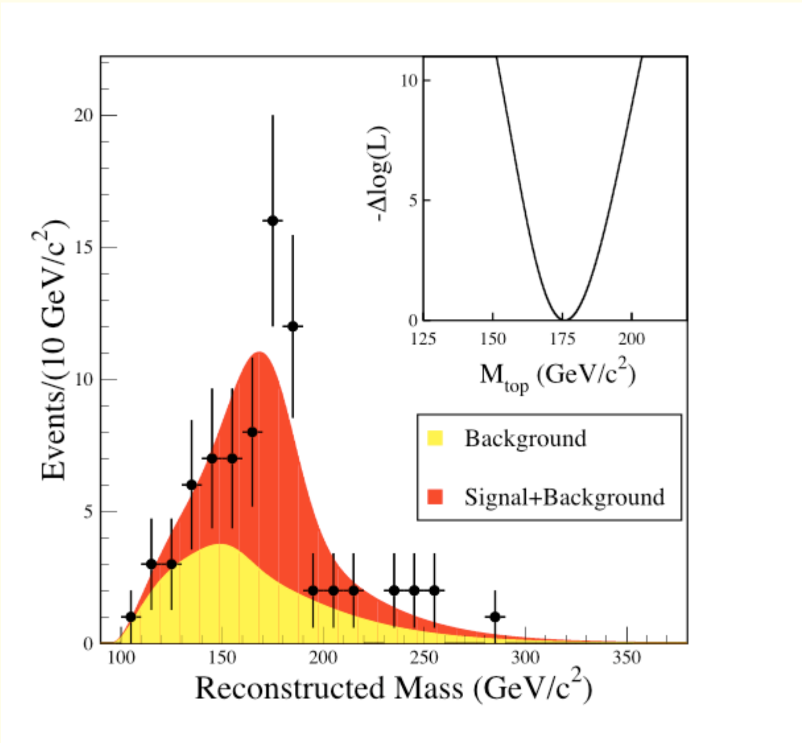
$$t \rightarrow W^{+}b$$



  - ***Garnered over 1,000 citations***

Properties of the Top Quark

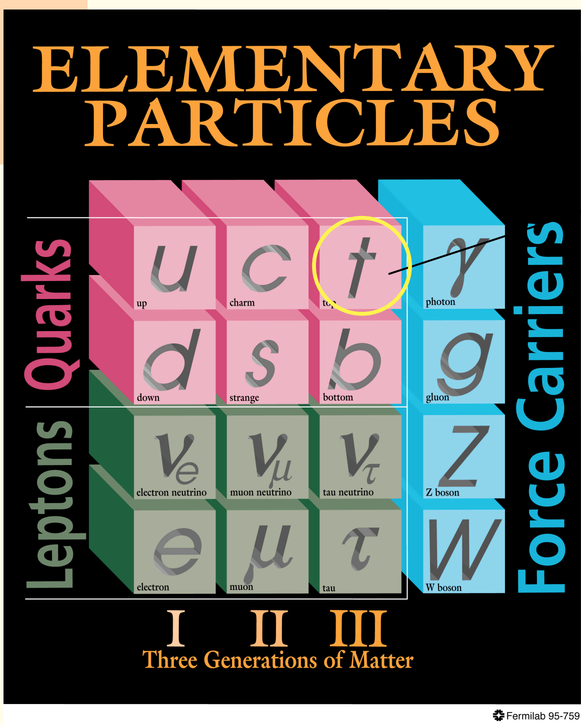
- ***Have seen the top quark decay to all expected final states***
  - ***Measured decay rates***
  - ***Measured production properties***
  - ***Measured its mass***



$$M_{top} = 176.1 \pm 6.6\, GeV/c^2 \quad (CDF)$$
$$M_{top} = 172.1 \pm 7.1\, GeV/c^2 \quad (D0)$$
$$M_{top} = 174.3 \pm 5.1\, GeV/c^2 \quad (RunI)$$

Our Picture of the Standard Model

- ***Summarize our "world view"***
  - ***Elementary building blocks***
  - ***Forces that act as the "glue"***



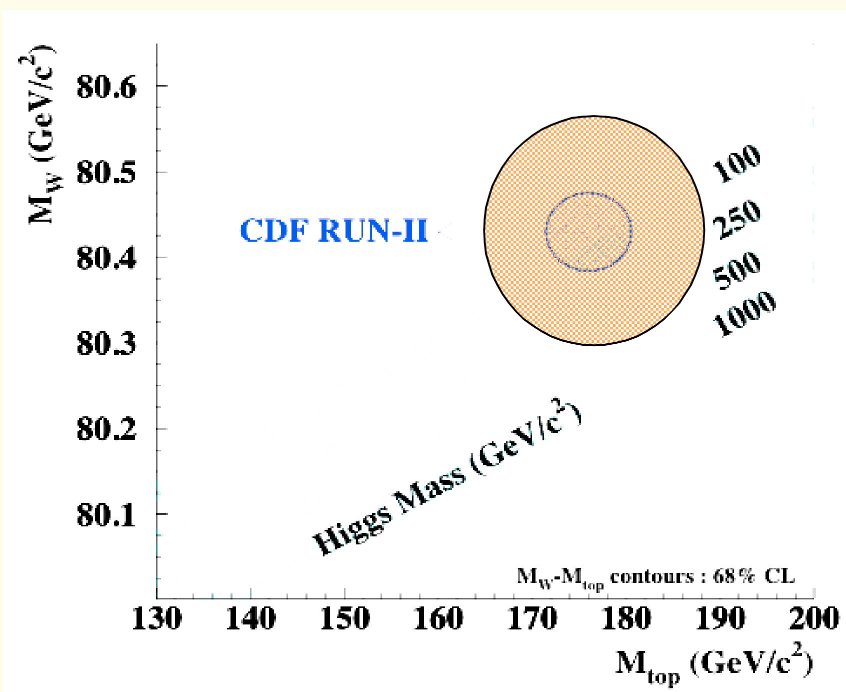
Discovered!

Many Questions Remain:
- Why 6 quarks?
- Why 6 leptons?
- Why the masses?

- ***And still missing the "Higgs" boson***

Search for "Truth" Continues

- ***CDF now CDF II***
  - ***Sequel collecting data now***
  - ***Improved detector & collider***
    - *Have almost doubled the sample now*
    - *Get 10 times more data in next 2 years!*
- ***Have ambitious goals***
  - ***Precision measurement of W boson and top quark masses***

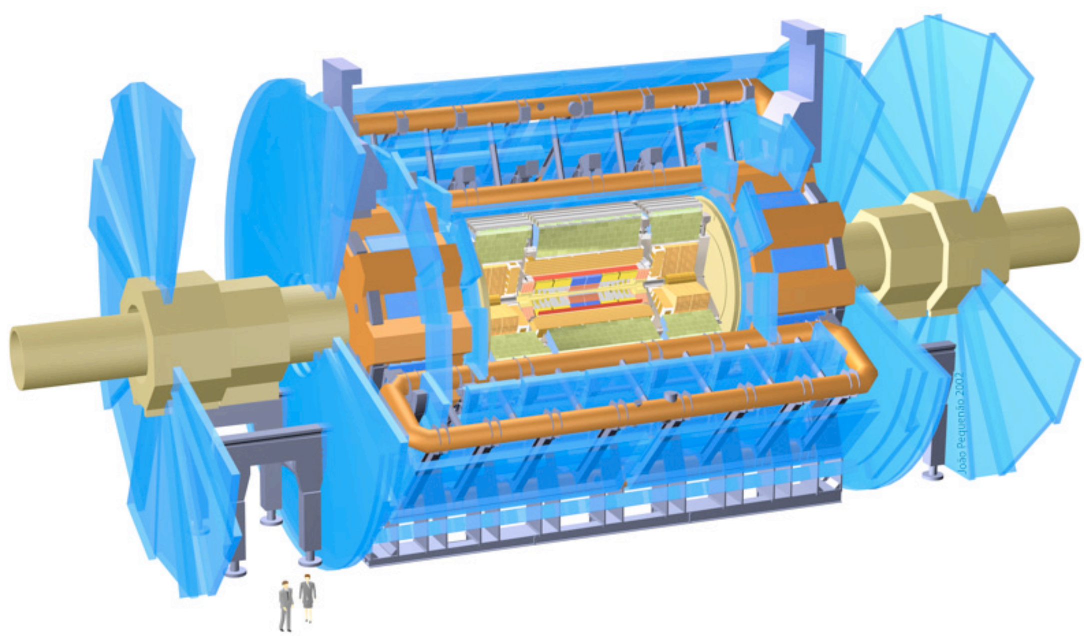


Large Hadron Collider at CERN

- **Collide protons together**
  - ***14 TeV total energy (7 x Fermilab!)***
  - ***Over billion collisions/second***
    - *Veritable top factory (1 Hz)*
    - *Aimed at nabbing the Higgs*

ATLAS Detector

- ***Group of 50 CDN scientists***
  - ***Played leadership role in experiment design***
  - ***Currently building components***
  - ***Developing computer systems and software for data analysis***



Canadian ATLAS Effort

- **_Contributed to the LHC_**
  - ***Series of power systems & magnets***

- **_CDN Components of ATLAS_**
  - ***Hadron Endcap & Cryogenic Feedthroughs***
  - ***Electronics***
  - ***Forward Calorimeter***
  - ***Software Development***

Toronto ATLAS Effort

- ***Just finished building part of Forward Calorimeter***
  - *Basement of McLennan Physics*
  - *Took two years of effort in clean room*

Building 4 modules
- *900,000 Tu slugs*
- *Copper matrix*
- *5-tons each*

Summary

- ***We have learned much about nature through studies of top***
  - ***First clear picture of "free" quark***
  - ***Properties confirm Standard Model***
    - *But leaves many questions open*
      - *What causes mass?*
      - *Why so many different particles?*
      - *What causes matter anti-matter asymmetry?*
      - *What makes up the rest of the mass in the universe?*
- ***But nature gives up its secrets reluctantly!***
  - ***Experiments challenging, with long timeframes***
  - ***Much yet to learn -- look for the first LHC results in 2008!***