The Stuff We are Made of

The Search for Fundamental Structure

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1. What Did We Know in 1900?
2. Studying the Fine Structure
3. Measuring the Size
4. Types of Bricks
5. Where All This Fits
6. What's Next?

Ernescliffe College
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$\boxed{\text{What Did We Know?}}$

Go back and review today's 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

- Leptons
- Hadrons

Some History About Structure

Lord Rutherford performed seminal scattering studies

- Looked at α scattering off gold (1911)
- Consistent with Coulomb scattering off point particle

$\Rightarrow$ Uncovered the nucleus

Hofstadter and colleagues extended this work

- Studied 1 GeV e^- scattering off nuclei (1953)
- Found that nucleus had extended charge distribution

$\Rightarrow$ shape of the nucleus

Taylor and colleagues probed more finely

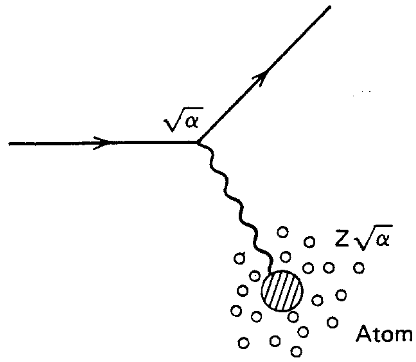
- Used $\sim$ 18 GeV e^- scattering off proton (1968)
- Found that nucleons were extended objects

$\Rightarrow$ discovered quarks!

About Rutherford Scattering

Rutherford developed classical theory of scattering

- Charged particle $Z_1 e$ scattering off nucleus Ze



- Define $\vec{q} = \vec{p} - \vec{p}'$, so that $q = 2p \sin\frac{\theta}{2}$
- Differential cross section is

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \frac{4m^2\left(Z_1 Z e^2\right)^2}{q^4}$$

- Correct classical and QM result ⇒ *Rutherford Scattering*

Discovered what we now call the **nucleus**

- To Rutherford, it looked like a point
- We now know it is $\sim 10^{-12}$ m in size

What Happens for Extended Objects?

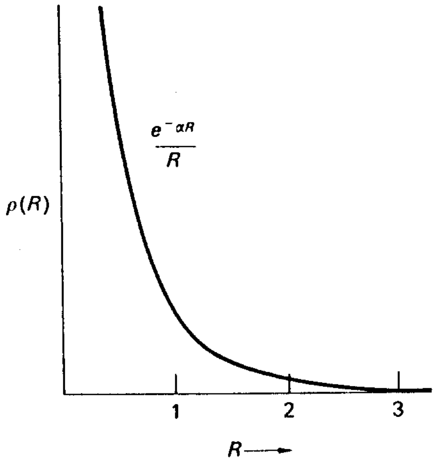
When scattering particle is extended in space

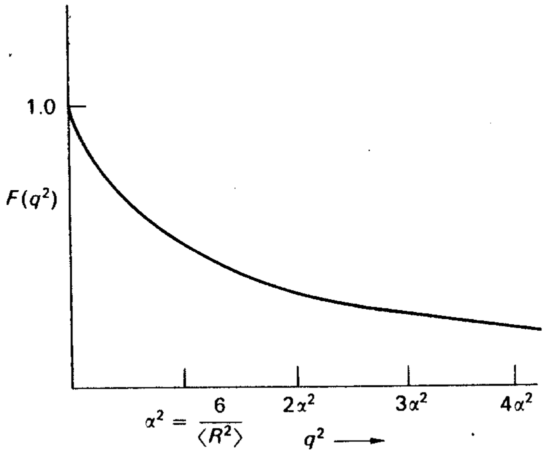
- Introduce "form factor" $F(q^2)$

$$F(q^2) = \int \rho(\vec{R}) e^{i\vec{q}\cdot\vec{R}} d^3\vec{R}$$

- Fourier transform of "charge" density ρ

$$\Rightarrow \left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{R}} \left|F(q^2)\right|^2$$



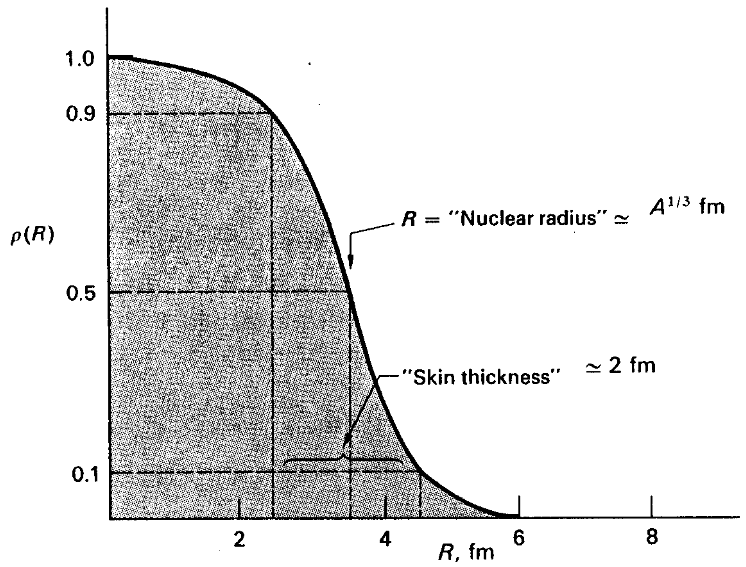


Nuclear Structure

Studies motivated by lousy understanding of nuclear forces (the "strong" force)

- Protons and neutrons are nuclear constituents
- Structure of nucleus was not understood
- Dynamics not well understood

Nuclear "charge distribution" obtained from $F(q^2)$



Tells us that nucleus is $\sim 2-4$ fm in "size"

Proton Structure

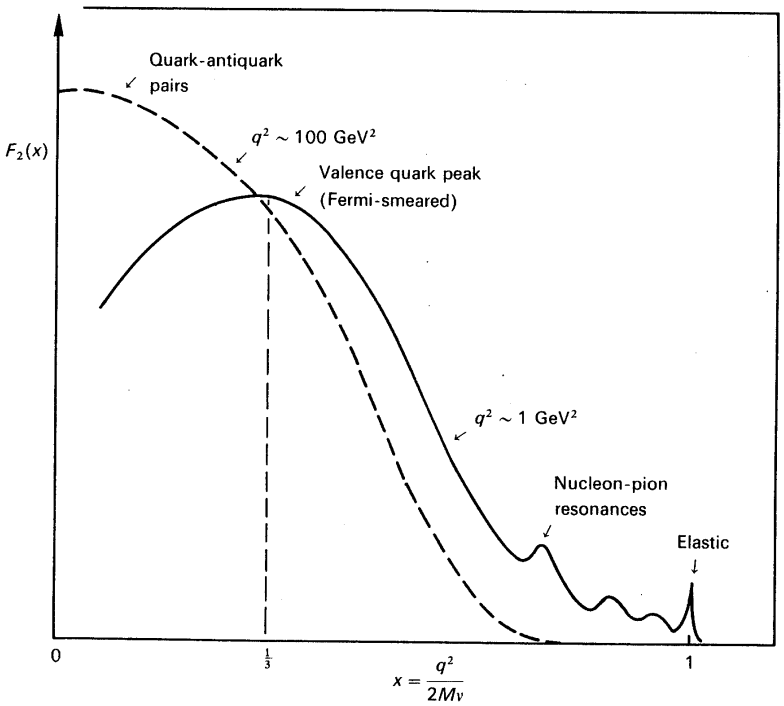
Deep inelastic $e^- p$ scattering reveals proton structure

- study inelastic part of cross section

$$e^- p \to e^- X_{\text{hadrons}}$$

  - suppress “coherent” and resonant nuclear scattering
  - Begin to see scattering off of constituents
  - Hitting partons with smaller x (x is momentum fraction)

- epitomised by “structure functions” $F_i(x, q^2)$

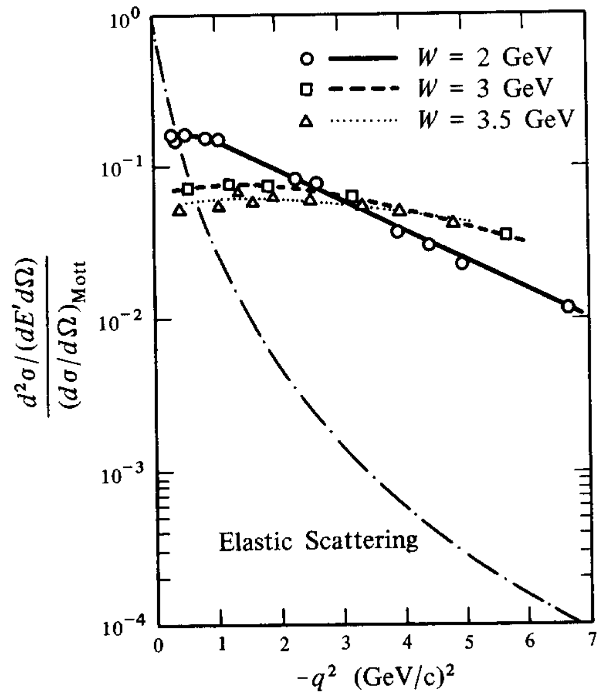


$$\left(\frac{d^2\sigma}{dq^2 dx}\right) \sim \frac{4\pi\alpha^2}{q^4}\left[(1-y)\frac{F_2(x,q^2)}{x} + \ldots\right]$$

Deep Inelastic Scattering Results

SLAC DIS studies revealed clear internal structure

- Evident as hadronic energy W increases (decreases x)



Detailed studies of structure functions F_1 and F_2 show

- Charge 1/3 and 2/3 particles
- Spin 1/2 particles
- Presence of anti-particles (the "sea")

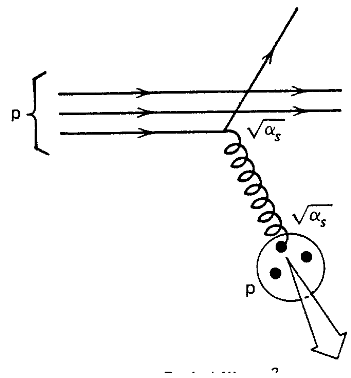
Quark Substructure?

Why would we think that quarks have substructure?

- Now 6(!) known flavours
- No reason 10^{-12} cm should be fundamental distance scale
- We don't believe that Standard Model is last word

To uncover structure, have to increase energy scale

- DIS limited by e^- energies and EWK nature of probe
- Need high-energy hadronic probe
  - closest to $q - q$ scattering is proton-proton scattering
  - Highest energies possible are at Fermilab Tevatron



Complications are that quarks are bound in proton

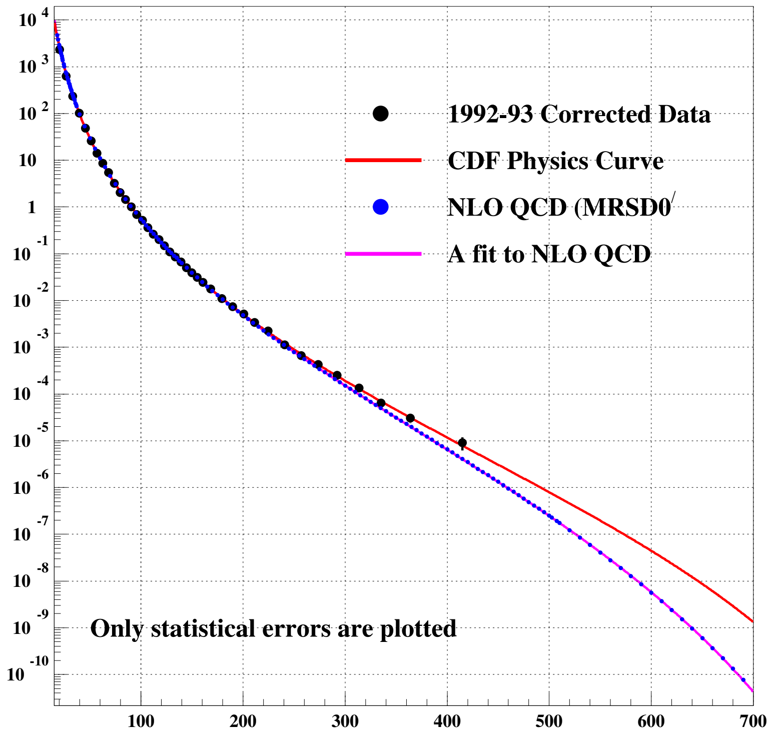
- Only have part of total energy available (x)
- Need to know distribution of quarks as function of x

Highest Energy Data

Typically look at energy distribution of "jets" produced in these collisions

- Compare with predictions that assume point quarks

Comparison of Corrected Data and NLO QCD

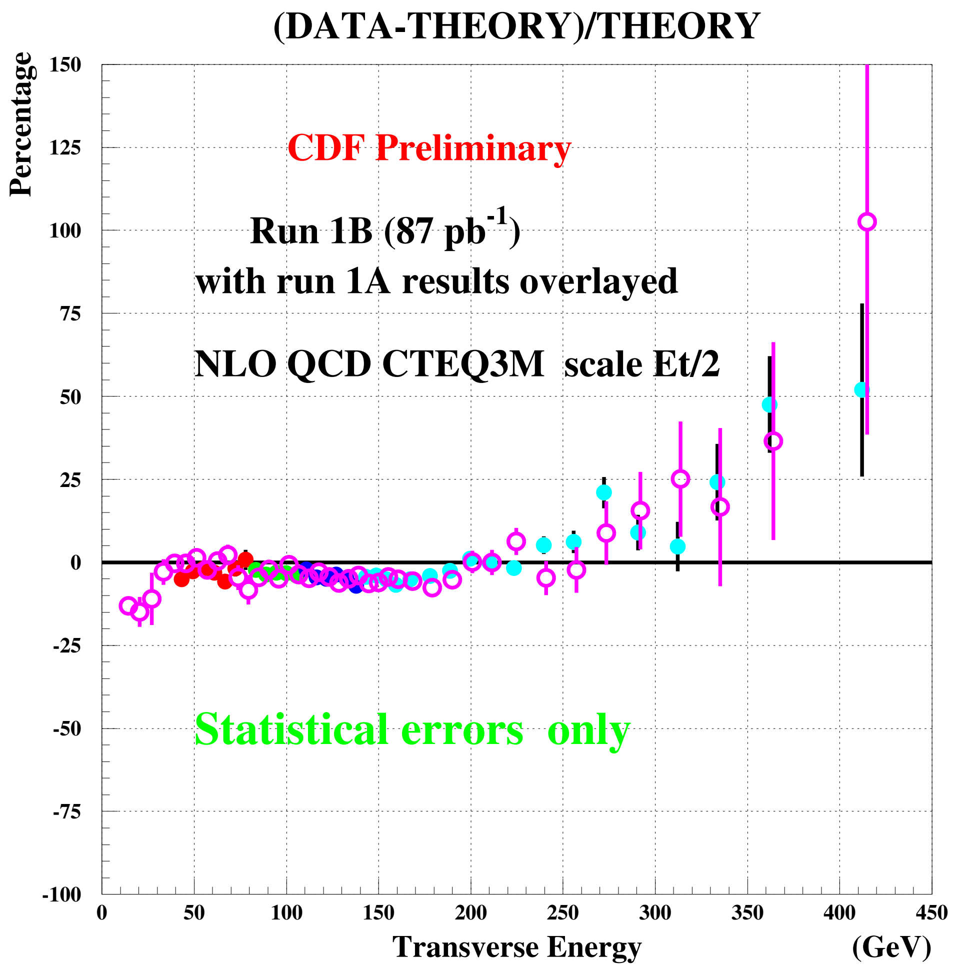


Physics Curve is well behaved beyond data
Parameterization also fits well to NLO QCD

High Energy Data

The high E_T tail does show an excess

- Best seen when comparing relative difference



One sees a small discrepancy

- Looks suspicious, but not conclusive
- Implies quark is smaller than $\sim 10^{-17}$ m

Bricks and Mortar

The "Standard Model" of Elementary Particle Physics

- Three "generations" of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

  Come in "pairs" because of the way forces acted on them

- Forces carried by bosons

Electromagnetic force	γ
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Strong force	eight gluons
Gravity	gravitons

- Quark and lepton mass due to "Higgs" particle

What We Knew in 1990

Leptons appeared fundamental

- electron is the most ubiquitous
- other leptons can be produced and studied
- neutrinos are particularly "ephemeral"

Predict that quarks only bind when you have

- three quarks (or three anti-quarks)
- a quark and an anti-quark

For example, a proton is made up of 3 quarks

- 2 up quarks
- 1 down quark

5 flavours $\Rightarrow$ get all known "elementary particles"

- This model works very well
- Predicts one more quark flavour – the top quark

What Was Missing?

Some pieces of this puzzle were not there

1. Expected "Unification" of forces
   - don't have a clue as to how to understand gravity
   - only have hints that forces are unified
2. Don't understand mass at all
   - "Higgs" boson has not been seen.....
3. Missing the last quark

But the rest of it worked extremely well!

- Many tests have been made over last 20 years

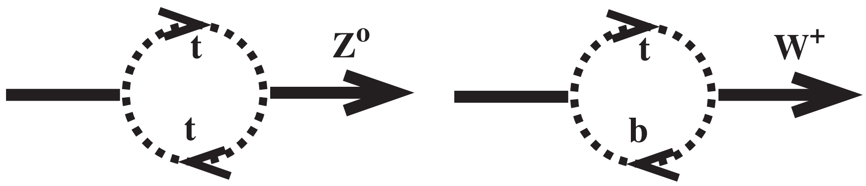
Challenge is to get data to address these questions

- $\Rightarrow$ Focus on the incomplete pieces

Why MUST the Top Quark Exist?

If top doesn't exist, the Standard Model crumples

- Masses of the $W^{\pm}$ and Z° bosons cannot be explained



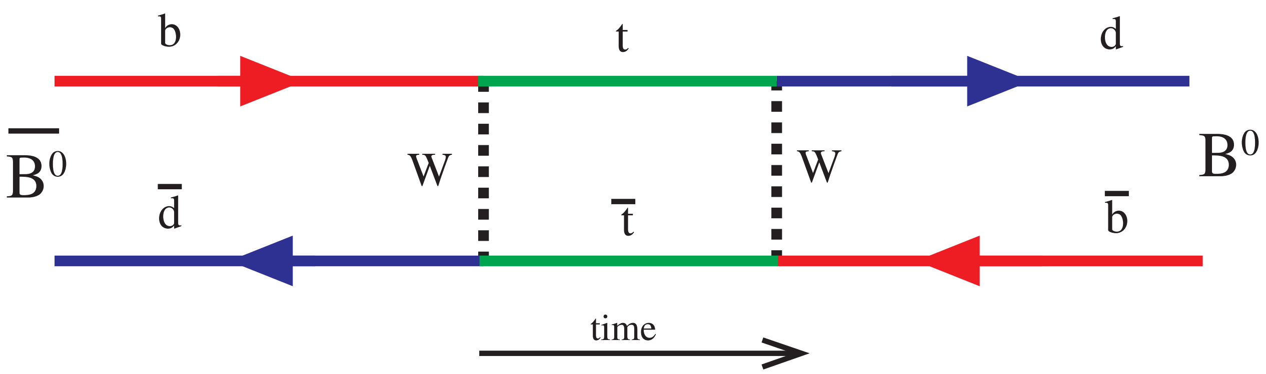
  – Measurements of the Z boson require

$$M_{top} = 166^{+17+19}_{-19-22}\ \text{GeV/c}^2$$

- Behaviour of the bottom quark implies that it must have a partner

  – Weak force predicts asymmetry in $e^+e^- \to b\bar{b}$

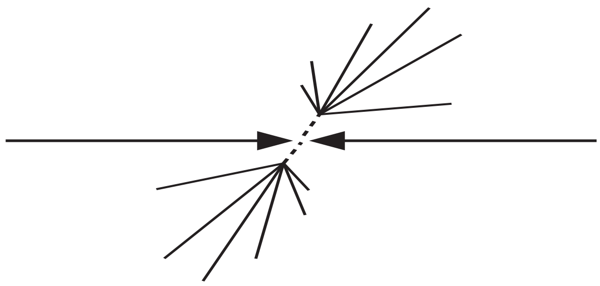
- B meson "mixing" could not occur



Searching for Top

Big Bang was last time nature created top quarks

- Can now pair-produce a heavy quark with enough energy
- Require high energy matter-antimatter collisions
- Need tons of data (they are rare events)



$p\bar{p}$ Collider at Fermilab was the "only" choice now

- High luminosities ($\mathcal{L} \sim 25 \times 10^{30}$ cm^{-2}s^{-1})
  - compare to radiation in this room $\mathcal{L} \sim 2{\times}10^{-2}$ cm^{-2}s^{-1})
- Highest energies ($\sqrt{s} = 1800$ GeV)
  - Enough energy to form fairly complex molecule
- Collected 3 million collisions

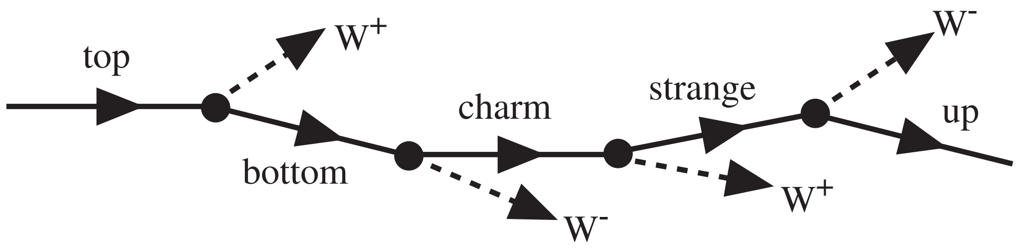
Why are Heavy Quarks Hard to Find?

Hard to produce

- Must sift through lots of matter-antimatter collisions
- Happens about 1 in every billion collisions?

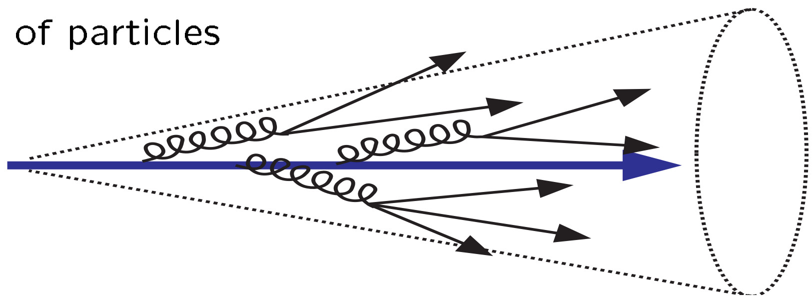
They Decay!

- A top quark decays via the weak force into a bottom quark
- The bottom quark then decays into lighter quarks



Ya can't see free quarks

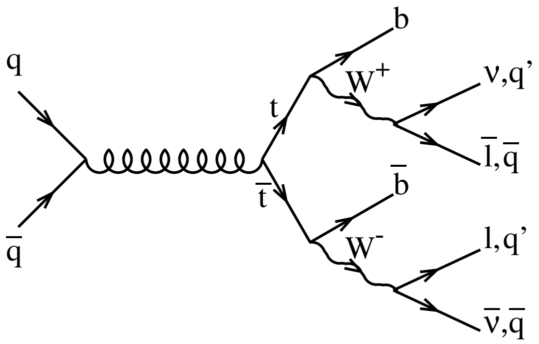
- Quarks are "not allowed" to appear unescorted in public
- Have to "dress" themselves up around other quarks
- Result in "jets" of particles



Top Quark Signatures

Top quarks only decay via the weak force

$$t \rightarrow W^+ b$$
$$\quad \hookrightarrow u\bar{d} \text{ or } c\bar{s}$$
$$\quad \hookrightarrow e^+\nu_e \text{ or } \mu^+\nu_\mu \text{ or } \tau^+\nu_\tau$$



This results in a number of very unusual "signatures"

- Can use these characteristics to sift the collisions

The CDF Experiment

CDF is detector designed to study $\overline{p}p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Large 5000 ton detector
- Think of it is a very big (expensive) microscope
  - Allows one to detect and measure the results of the collisions

Collaboration consists of

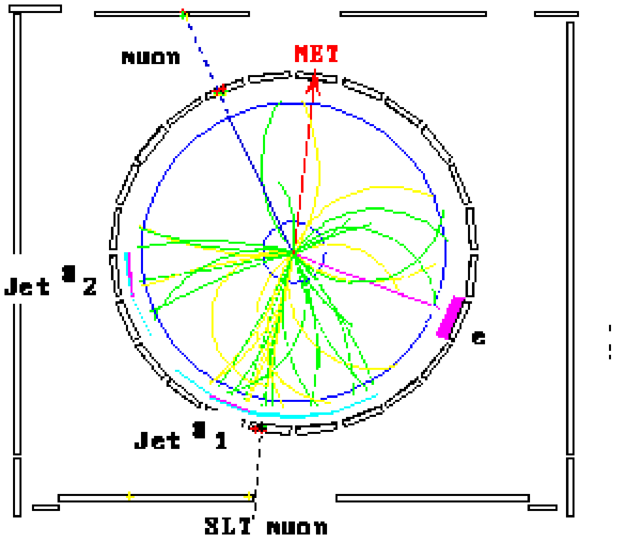
- 35 institutions from US, Japan, Italy, Canada and Taiwan
- 450 physicists

Why so many people?

- takes enormous scientific effort to mount experiment
- continual improvements and repairs

Now Have the Evidence...

In about 10 billion collisions, find about 50 events



We observe about the right number of different types

- Observe 1 $\mu^+\mu^-$ event and 5 $e\mu$ events
- Expect 1.3 ± 0.3 events from background
- Observe ~ 40 events with $W+ \geq 3$ jets

Probability of background looking like this is $< 10^{-6}$

What's Next in the Quark World?

Continuing to take data and get more top quarks events

- measure its properties
  - mass
  - how it decays
  - how it gets produced
- All provide additional tests of the theory

Still at least one missing piece – Higgs Boson

- Quest for that is now beginning
- Building a new proton-proton collider in Geneva
  - Large Hadron Collider
  - 7 times more energetic than Fermilab Tevatron
  - 100 times higher collision rate
  - experimental teams have over 1000 scientists
- But don't hold your breath
  - Turn-on scheduled for 2004!

So What?

Top quark discovery is a triumph of the Standard Model

- validates 17 years of work
- ends a great deal of speculation
- strong indication that we are on the right track
  - focus on remaining pieces of puzzle now

We have no idea of the practical benefit this will bring

- basic research is something like Pandora's Box
- history has shown that basic research eventually has impact
  - totally unpredictable
  - impossible to value accurately

Why Are These Questions So Important?

Humanity seems to be “driven” to wonder

- We seek out frontiers
  - Physical challenges
  - Intellectual challenges
- Is there somethere out there we don’t understand?
  - science allows us to focus our questions
  - ask what appear to be the “best” questions
- We question where we fit in?

Push our technological frontier

- This physics is the most “basic” of basic sciences
- Historically, very rich in spin-offs
  - Nuclear medicine, imaging
  - Smoke detectors and other sensors
  - Nuclear power, weapons
  - Large scale data processing

  ...... List goes on

Presents some of the greatest intellectural challenges

- Attracts some of our most creative and energetic people
- Allows one to leave a “mark” on our world

Summary

Haven't reached the end of the story

- Many open questions, for example
  - What and where is mass?
  - What really are quarks? leptons? neutrinos?
  - How did our universe become what it is today?

But we are making progress

- We have a "picture" that works pretty well already
- Focusing on those pieces that don't quite fit

Soon we hope to have a much better understanding of

- the bricks,
- the mortar,
- ...and what nature builds with it.

Consider Now the Quark

Consider now the Quark, which is
        A Concept sub-atomical.
No man alive has seen its phiz;
        Perhaps it isn't Is at all.

A Concept sub-atomical
        Too tenuous I find to prove.
Perhaps it isn't Is at all.
        This goes for Hate, and also Love.

Too tenuous I find to prove
        The Sun, the Shadow, and the Wind.
This goes for Hate, and also Love.
        And other matters of the kind.

The Sun, the Shadow, and the Wind.
        The Dream, the Doing, the Depair,
And other matters of the kind
        I find are proven best in prayer.

The Dream, the Doing, the Despair,
        And other matters, being His,
I find are proven best in prayer.
        Consider now the Quark, which Is.

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