Quarks and Cosmos

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1. What is Our World Made Of?

2. The Big Questions We Face

3. Some Answers....finding a new quark

4. What's Next?

Learning Unlimited
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The Structure of Our World

I look at our world as having 3 distinct distance scales

1. Very largest scales
   - Size of the known universe ($\sim 10^{25}$ m)
   - Galactic clusters ($\sim 10^{22}$ m)
   - Galaxies ($\sim 10^{21}$ m)
   - Solar System ($\sim 10^{13}$ m)
2. "Mushy" intermediate scales
   - The Earth ($\sim 10^{7}$ m)
   - You and me (~ 1 m)
   - Virus ($\sim 10^{-7}$ m)
3. Very smallest scales
   - Molecules ($\sim 10^{-9}$ m)
   - Atom ($\sim 10^{-10}$ m)
   - Nucleus of an atom ($\sim 10^{-14}$ m)

Big differences in the natural structures

- But very largest and smallest scales very similar
  - "simple" structures
  - have very related problems

$\boxed{\text{What Are Quarks?}}$

Go back and review 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

- Find that these are made up of smaller objects
- Those are what we call quarks...

How It All Works (circa 1980)

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

Building up Elementary Particles

Leptons are already fundamental

- electron is the most ubiquitous
- other leptons can be produced and studied

Predict that quarks only bind when you have

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

For example, a proton is made up of 3 quarks

- 2 up quarks
- 1 down quark

With 5 types of quarks, we get all the known "elementary particles"

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

$\boxed{\textbf{This is Very Pretty...}}$

Only have to know how the quarks and leptons behave

- Measure their properties
- Measure the forces that act on them
  - three of the forces should be different aspects of the same interaction

Now can build up our understanding of everything else

- A proton is made up of uud
- A neutron is a udd combination
- Can work out how nuclei of atoms work
- ...then atoms themselves
- ...then molecules, and so on....

And its all based on three ingredients (u, d, and e^-)

What's Missing

But not all the pieces of this puzzle are there

1. "Unification" of forces hasn't panned out
   - 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
   - Enter the "Higgs" boson.....
3. Missing the last quark

But the rest of it works extremely well!

- Many tests have been made over last 20 years

To learn more, have to "test" the theory

- $\Rightarrow$ search for the missing pieces

The Cosmos?

The "Cosmos" is our world on a universal scale

- Made up of "globs" of matter
- We see the so-called "luminous" matter
  - stars
  - galaxies and galactic clusters
  - "sheets" and "voids"

Everything is just matter (and anti-matter)

- Only significant force is gravity
- Should be simple to understand

But what we observe is a system that is changing

- Appears to be expanding
  - farthest stars are moving very rapidly
- Has structure that evolves

$\boxed{\text{What's Wrong With This Picture?}}$

Missing Mass Problem

- Can measure the mass of our galaxy using
  1. luminous matter (stars and dust clouds)
  2. indirectly from gravitational forces
- Seems like there is about $\times 10$ more matter than is visible!

Formation of Large-scale Structures

- The expanding universe implies a beginning
  - "Big Bang" – just pure energy
  - Maybe 10-20 billion years ago
- Structure had to start forming very early
  - Too early to make sense

The Cosmic Contradiction

The Big Bang happened –

- just energy (matter and anti-matter) to begin with
- "hot soup" rapidly expanded and cooled
- protons and neutrons formed in 1 s
- atoms started forming after about 300,000 years
  - radiation and matter stopped interacting
  - radiation continued cooling undisturbed
  - matter then started forming structure

Radiation is still kicking around today

- Cosmic microwave background discovered in 1965
- Has a temperature of about 3° K (-270° C)
- Turns out to be VERY smooth

Implies Universe was also smooth at 300,000 years

- Can't explain the large structures we see
- Need at least small "ripples" that then grow

The Big Questions?

1. How many building blocks (quarks and leptons)?
2. What are the forces?
3. What is mass, and in what form is it?
4. How does cosmic structure form?

Has been progress on some of these questions

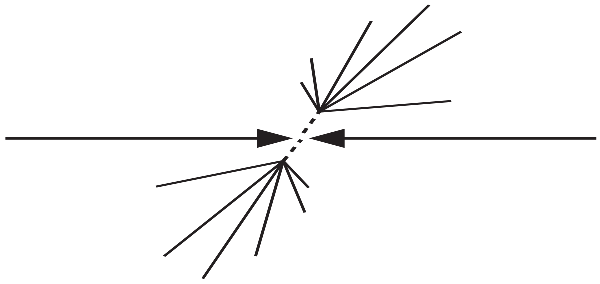
- We recently nailed down one “missing” quark
  - We discovered the top quark

But most of these questions remain unanswered.....

Searching for Top

A heavy quark can be pair-produced in collisions

- Require high energy matter-antimatter collisions
- Need tons of data (they are rare events)



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

- High luminosities ($\mathcal{L} \sim 25 \times 10^{30}$ cm^{-2}s^{-1})
  - compare to radiation through this room $\mathcal{L} \sim 2\times10^{-2}$ cm^{-2}s^{-1})
- Highest energies ($\sqrt{s} = 1800$ GeV)
  - Enough energy to form fairly complex molecule

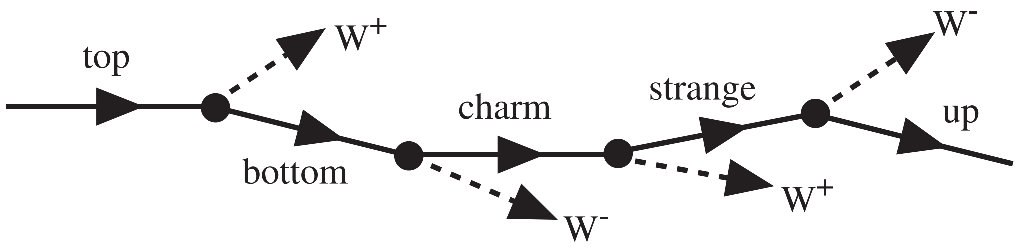
Why are Heavy Quarks Hard to Find?

Hard to produce

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

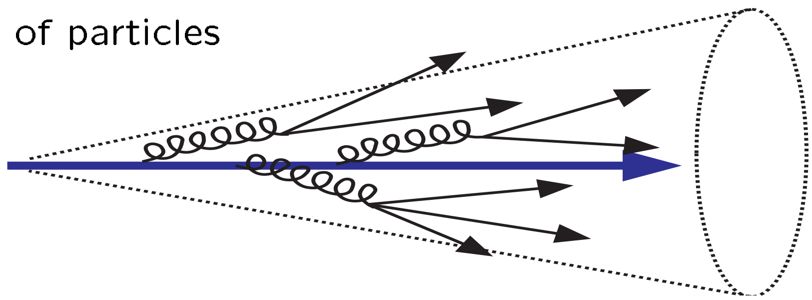
They Decay!

- 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



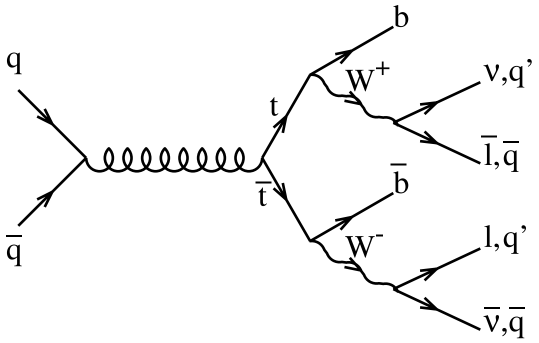
Top Quark Signatures

Top quarks only decay via the weak force

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

$\hookrightarrow u\bar{d}$ or $c\bar{s}$

$\hookrightarrow e^{+}\nu_{e}$ or $\mu^{+}\nu_{\mu}$ or $\tau^{+}\nu_{\tau}$



This results in two, potential signatures

- Dilepton events with two, energetic $e^{\pm}$ and $\mu^{\mp}$
- Lepton + Jet events with at least one b quark

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
- 440 physicists

1992-94 Collider Run

Took data at the Tevatron Collider starting in 1992

- scanned $\sim 5 \times 10^{12}$ collisions
- Collected 50×10^{6} events on tape

Most sensitive dataset acquired to date

- If top exists with a mass of 160 GeV/c^2
  - Expect 5000 produced $t\bar{t}$ events
  - Should observe 5 dilepton events
  - Should observe 10 lepton + jet events

Dilepton Top Quark Search

$t\bar{t}$ decaying into 2 leptons create unique signature

- Two charged leptons from $W^{\pm}$ decay
- Imbalance in total energy due to undetected neutrinos
- Two jets from bottom quarks

Observe a total of 6 candidate events

- Observe 1 $\mu^{+}\mu^{-}$ event and 5 $e\mu$ events
- Expect 1.3 ± 0.3 events from background

Probability of background fluctuation is 3.3×10^{-3}

$\boxed{\text{Lepton + Jets Search Philosophy}}$

Decay mode with the greatest sensitivity is "lepton+jets"

- About 30% of $t\bar{t}$ events decay this way
- Look for $W \to l\nu_l$ decay
- Require two jets from $W \to q\bar{q}$ decay
- Require at least one more jet from b quarks
  - must "tag" at least one b quark jet

Searched for these types of $W+ \geq 3$ jet events

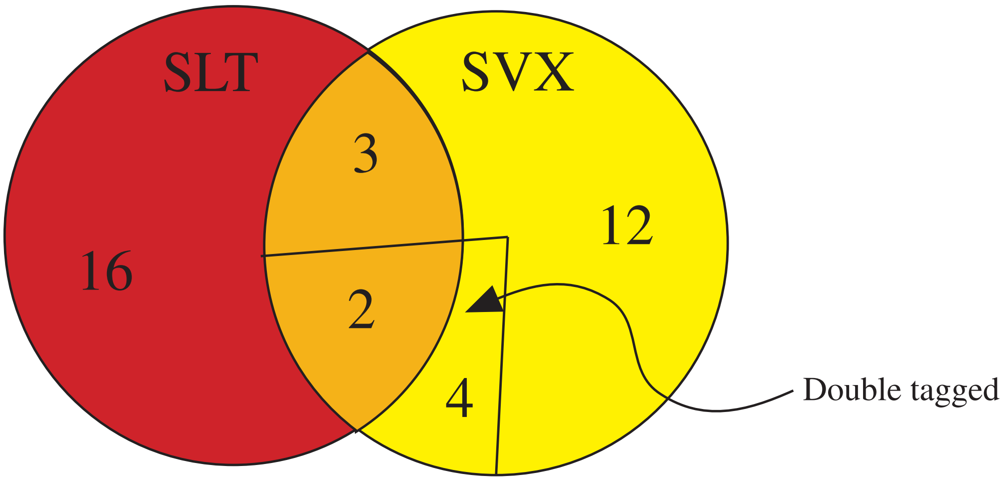
- Have 203 events before b tagging
- Expect ~ 30 to come from $t\bar{t}$ production
- Get rid of rest by looking for a b quark

b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+$\geq$ 3 jet	6.7 ± 2.1	27	15.4 ± 2.3	23

- Probability of background fluctuation is 1×10^{-6}
- Agrees well with expected rate from $t\bar{t}$ production



Is This a Discovery?

Tough question to answer

- Sure don't want to be wrong
- On the other hand, don't want to avoid the facts

In February, agreed that we were observing something new

- probability of "being wrong" extremely low
- exactly what we expected to find

Checked the data in lots of ways

- Everything points to the same conclusion
- Another experiment has also looked and agree with us

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!

Quarks and Cosmology Revisited

We now have what appear to be complete families of quarks and leptons

- six types of quarks
- six types of leptons

Solution to missing mass or structure problem not here

- Our best guess now is that the answer is either
  - neutrinos don't behave correctly
  - there exist some undiscovered type of matter

Some other clues that seem to implicate neutrinos

- Too few coming from the sun
- Sudbury Neutrino Observatory being built to check this

Summary

Haven't reached the end of the story

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

But we are making progress

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

Soon we will have a much better understanding of

- the very big,
- the very small,
- ...and all that we find in between!

So Why is This Important

It won't lead to a "better mousetrap?"

No, but that's not what we're all about

- Important to understand how our world works

But for those who don't like this answer....

- the following resulted from "basic research"
  1. nuclear medicine (and warfare...sigh)
  2. the transistor
  3. gene research
  4. antibiotic drugs

Basic questions remain about our world

- Much to be understood in our future work