The Discovery of Truth: How the Top Quark was Found

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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

- Quark and lepton mass due to “Higgs” particle

$\boxed{\textbf{Building up Elementary Particles}}$

Leptons are already 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's Missing

Some pieces of this puzzle are 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 works extremely well!

- Many tests have been made over last 20 years

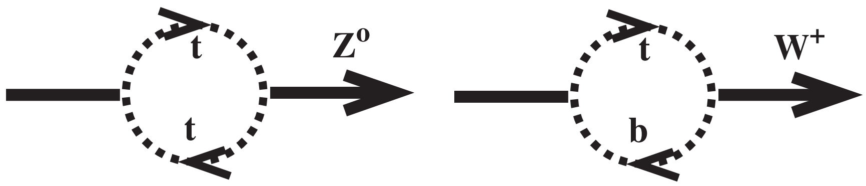
To learn more, have to "test" the theory

- $\Rightarrow$ search for the missing pieces

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

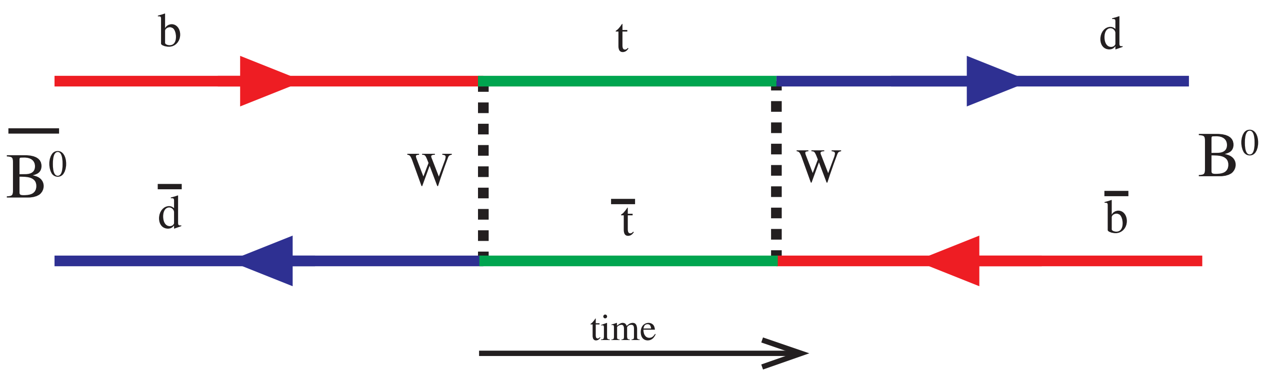


  - Measurements of the Z boson require

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

- 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

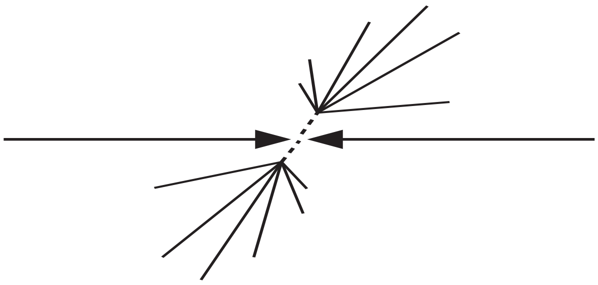


Searching for Top

Big Bang was last time nature created top quarks

Can 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 is the "only" choice

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

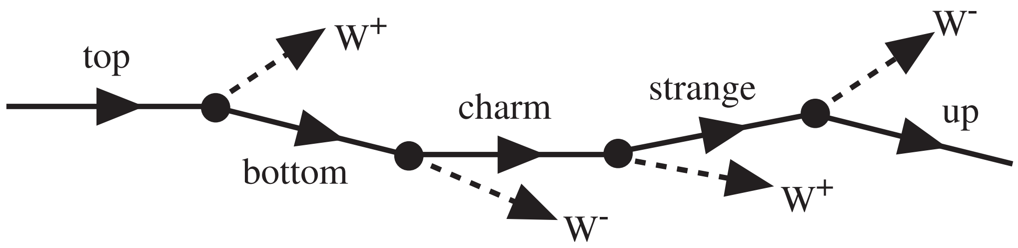
Why are Heavy Quarks Hard to Find?

Hard to produce

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

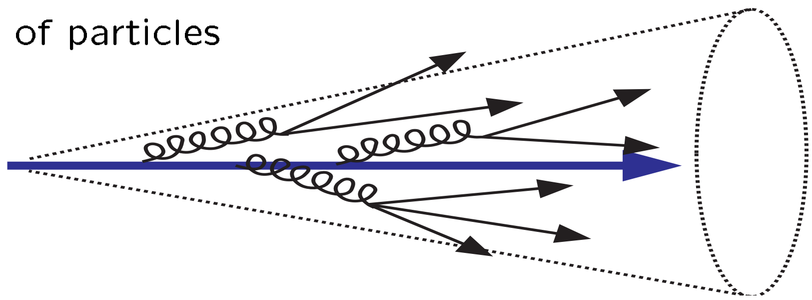
They Decay!

- 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



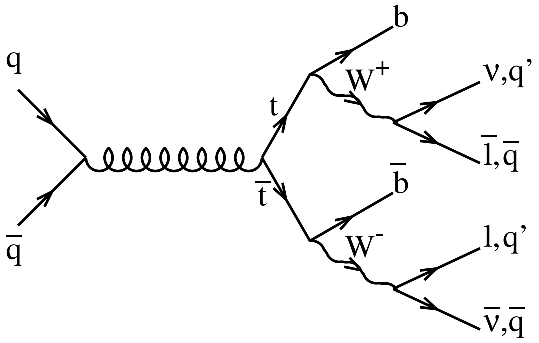
Top Quark Signatures

Top quarks only decay via the weak force

$$t \rightarrow W^+ b$$

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

$\quad\quad\hookrightarrow e^+\nu_e$ 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
- 450 physicists

Why so many people?

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

1992-95 Ferilab 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

If we couldn't find it here, we weren't going to...

- 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

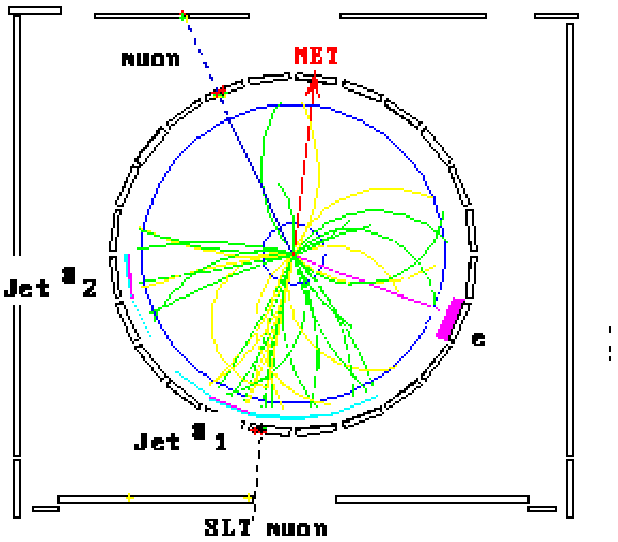
Have to realise that there was competition...

- Another collaboration taking similar data

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



We 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}

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

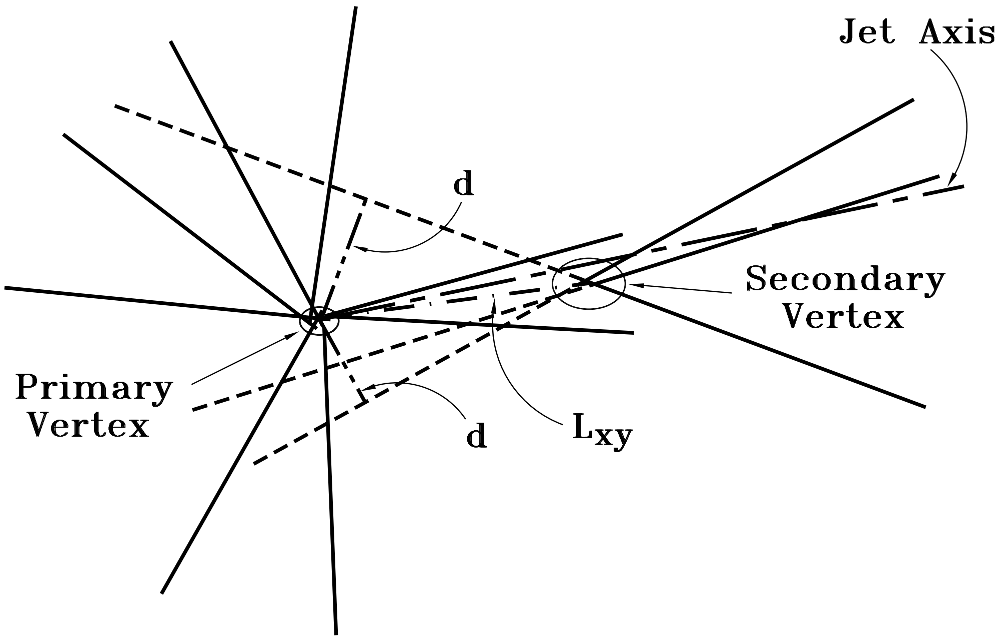
Tagging Bottom Quarks

Use two properties of b quarks to identify them

1. "Long" b lifetime – $c\tau \sim 450$ microns

   - Use Silicon Vertex Detector (SVX) to identify jets with a secondary vertex

   - Expect 42% of $t\bar{t}$ events to have at least one SVX tag



2. About 20% of b's decay via

$$b \to e^- \nu_e X \quad \text{and} \quad b \to \mu^- \nu_\mu X$$

   - Look for jets with "soft" leptons in them (SLT tags)

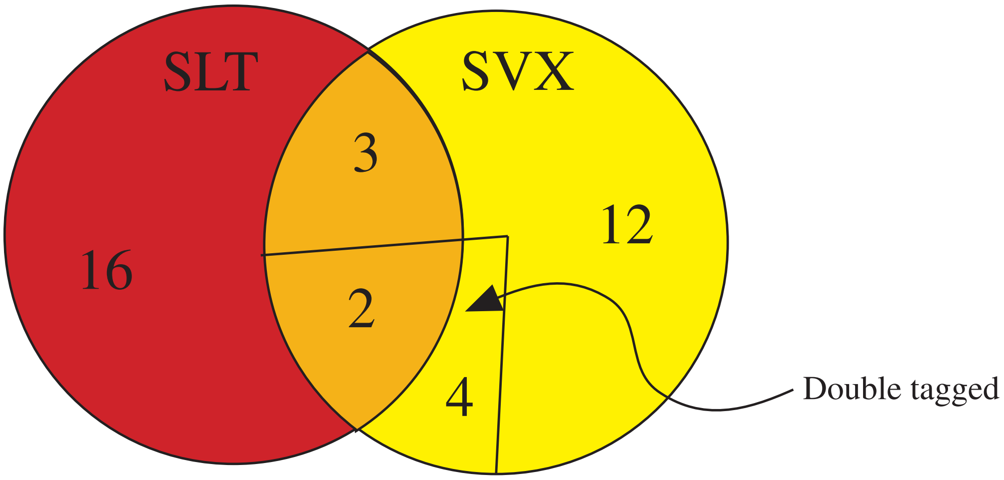
Idea is to just "count" number of tagged events

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

Spent close to a year working on initial data analysis

- Published first report of "evidence" in April 1994
- Took more data ($\times 3$ more)
- Agreed that we had "discovered" top in February 1995
  - 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
- Determined that top quark mass was 175 ± 13 GeV/c^2
- The "other" experiment also looked and agreed with us

What Was the Competition Saying?

Skepticism after we published "evidence"

- Responded with a report on their data
- Not as sensitive as our experiment
- Did not find a contradiction

In March 95, when we had decided to go with it

- Gave them a week's notice (lab policy)
- They agreed with our interpretation
- Published a report in same journal issue

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!

$\boxed{\text{So What?}}$

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

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 building blocks,
- the glue,
- ...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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