To the Top and Beyond:
Particle Physics
and the New Century

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What is the world made of? What holds the world together? Where did the universe come from?
What is the World Made Of?
Ancient Greeks

Empedocles (490–430 BC)

Four Fundamental elements

Democritus (460–370 BC)

Atoms: Indivisible, Space between

Fire
Air
Water
Earth

(c) Andy Brice 1998
“By Convention there is color, 
by convention sweetness, 
by convention bitterness, 
but in reality there are atoms and space.”

-Democritus (400 BC)

Atom = Mushy Ball (c. 1900)
Depths of Matter

Aristotle (384-322 BC)

Dalton, 1803

Mendeleev, 1869
J.J. Thomson
J.J. Thomson, 1895

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of a hydrogen atom?”
Electron is Discovered!

J.J. Thomson, 1895

"Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of a hydrogen atom?"
What are Atoms Made of?

“Plumb pudding”

Thomson Model of the Atom
First Particle Physics Experiment

Atomic model circa 1905

Ernest Rutherford
Rutherford’s Experiment, 1909

Rutherford expected:

beam of $\alpha$ particles

(Geiger and Marsden: grad students)
Rutherford’s Experiment, 1909

He found:
beam of \( \alpha \) particles

Led to new model of atom

\[
\frac{\text{Nucleus}}{\text{Atom}} = \frac{\text{Fly}}{\text{Cathedral}}
\]

‘like a fly in a cathedral’
Once we glimpsed the fly in the cathedral, we needed to know more, to catch it, examine it, dissect it!

What is nucleus made of?

a single fundamental particle? - many of them?

made of a smaller thing or smaller things?

different nuclei = different quantities of ‘same’ small things?
What is the World Made Of?

From atoms to electrons and nucleons... what smaller?
Need Powerful Tools to See Tiny Things
Seeing it at 100 times smaller scale
pollen

Another 100 times smaller
Optical Microscope using beam of light

Another 100 times smaller

0.01 mm

bacteria
Needed to change technology.

Another 100 times smaller

Electron Microscope using beam of particles (small accelerator)
Atoms in DNA

X Ray machine

Needed to change technology again.

using beam of x-rays (accelerator!)

Another 100 times smaller

0.000001 mm

Atoms in DNA
Rutherford Discovered the Nucleus using a beam of alpha particles

He found:
beam of $\alpha$ particles

To probe deeper: Needed to use smaller particles as probes! The birth of particle accelerators…

Rutherford Discovered the Nucleus using a beam of alpha particles
(Alpha particles are Helium Ions)
Use Accelerators as Powerful Microscopes

They make higher energy *particle beams* that allow us to see smaller things.

seen by low energy beam *(poorer resolution)*

seen by high energy beam *(better resolution)*
Many campuses began to build accelerators to study subatomic particles.
New Types of Matter…

1950s and ‘60s: Zoo of particles found, various properties…
→ Is there a pattern?
The Quark Idea

“Three quarks for Muster Mark!”

1964

What if 3 smaller particles with different charge and properties combine together to explain this zoo?

*Finnegan’s Wake, J. Joyce*
The Stanford two-mile electron linear accelerator (SLAC)
Quarks detected: 1968!

Experiments conducted from 1966-1978 by Richard Taylor (SLAC), Henry Kendall (MIT), and Jerome Friedman (MIT) studied how high-energy electrons bounce off the protons and neutrons in a target. Their results showed more electrons bouncing back with high energy at large angles than could be explained if protons and neutrons were uniform spheres of matter.
Quarks are Found!

Quarks detected: 1968!

1990 Nobel Prize in Physics: Quarks Revealed!

Structure Inside Protons and Neutrons
Peeking inside the atom...

Video clip
~90 years ago

1\times 10^{6} of human hair thickness

~60 years ago

1\times 10^{3}

~40 years ago

1\times 10^{4}

Present

1\times 10^{5}
What is the World Made Of?

What, then, is fundamental?
The Nature of Matter

Could there be more quarks? Or something smaller?

Structure within the Atom

Quark
Size $< 10^{-19}$ m

Electron
Size $< 10^{-18}$ m

Neutron and Proton
Size $= 10^{-15}$ m

Nucleus
Size $= 10^{-14}$ m

Atom
Size $= 10^{-10}$ m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Atoms as we know them today
What Holds it all Together?

Gravitational Force
- Issac Newton (1642 - 1727)
- Graviton

Electromagnetic Force
- James Clerk Maxwell (1831 - 1879)
- Photons (γ)

Gravitational Force

Electromagnetic Force
Weak Force

Strong Force

radioactive decays

W/Z bosons

neutron decay

holding proton, nucleus

gluons

Enrico Fermi (1901 - 1954)
Four Fundamental Forces

“Mediated” by particles called bosons!

* Graviton not discovered yet.
Meanwhile…

Quarks found: 1968!
Meanwhile...

Long Island, NY

Menlo Park, CA

Quarks found: 1968!
Meanwhile...

Quarks found: 1968!
Meanwhile...

Quarks found: 1968!

Geneva, Switzerland
Quark Discoveries

- Quarks (u, d, s) were postulated in 1964, discovered at SLAC in 1968
- The charm quark c was discovered in 1974 by Brookhaven and SLAC
- The bottom quark b was discovered in 1977 at Fermilab

The bottom quark needed a partner... and the race was on!
Race for the Top Quark

• 1974 - Charm quark discovered (Brookhaven/SLAC) at 1.2 GeV
• 1977 - Bottom (beauty) quark discovered (Fermilab) at 4 GeV.

Top quark expected at 15-20 GeV!

• 1979 - 1989 PEP collider (SLAC), PETRA collider (Germany), TRISTAN collider (Japan) all ruled out top (truth) at < 30 GeV.
• 1983 - SppS proton collider at CERN discovered W, Z bosons!
• 1988 - 1989 Tevatron collider (Fermilab) ruled out top < 72GeV.
• 1982 - 1989 Spps ruled out top at < 69 GeV.

Game over!

Everyone wanted the “truth” first!

Fermilab only could reach the energy needed…
CLIMBING THE WORLD'S 14 HIGHEST PEAKS

NO SHORTCUTS TO THE TOP

ED VIESTURS WITH DAVID ROBERTS
Top Quark Discovered!

1994 - 1995

175 GeV!
Discovery is Exciting!

Adding something to the core of human knowledge is profoundly satisfying.
The Standard Model

Periodic Table of the Particles

<table>
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<th>mass, GeV</th>
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<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^3$</td>
</tr>
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</tr>
<tr>
<td>$10^1$</td>
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<tr>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>$10^{-11}$</td>
</tr>
</tbody>
</table>

- **Quarks**
  - $u$
  - $c$
  - $t$
  - $d$
  - $s$
  - $b$

- **Leptons**
  - $e$
  - $\mu$
  - $\tau$
  - $\nu_e$
  - $\nu_\mu$
  - $\nu_\tau$

- **Forces: Bosons**
  - $g$
  - $W$
  - $Z$
  - $\gamma$

5 orders of magnitude!
Accelerators

Accelerators are our tools to discovery!
We can create particles with very large masses, and explore Nature beyond what exists today.

\[ E = mc^2 \]
Modern Particle Accelerators are *Gigantic!*

PEP-II, SLAC, Palo Alto, USA

KEKb, KEK, Tsukuba, Japan

HERA, DESY, Hamburg, Germany

Tevatron, Fermilab, Chicago, USA
Tesla Coils
Accelerators achieve more than a million times these energies!
All Sped Up!

“It started with just the particles being Accelerated, but now everything Around here has speeded up!”
Where Top Quarks are Produced

Fermi National Accelerator Laboratory, near Chicago, IL
World’s Most Powerful Accelerator: Fermilab’s Tevatron

- Main Injector
- Tevatron Ring (~4 miles)
- Booster
- CDF
- DØ

- Chicago
Chain of Accelerators
Video clip
The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.
Challenges

trillions of particles in beams ~ speed of light

2 million collisions per second

one out of one million
top

one out of ten billion

thickness of human hair
Proton / anti-Proton Collisions

Video clip
Collisions Producing Top Quarks!
How we “see” particles

Most collider detectors are similar...
How we “see” particles

Video clip
Tevatron’s CDF Detector
One piece of the detector has 30,000 high-voltage wires thickness of human hair
Top Re-Discovered

Turn of this century… Tevatron “Run 2”
Studying the Top Quark

- Mass of Top Quark?
- How often is it produced?
- How does Top decay?
- What is its lifetime?
Top quarks are one of the more sexy things to study at the Tevatron

I work with quarks.

Oooh... I'm getting all goosebumpy.

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.
“Why are there so many particles?”
“Where does mass come from?”
Higgs Boson

Not yet discovered!!!

Standard Model predicts a new, 5th interaction.

→ The hunt for Higgs is underway!
Top is Pointing to the Higgs?

- W boson mass
- Top quark mass

Higgs Mass?!
Top is Pointing to the Higgs?

W boson mass

Higgs Mass?!

Top quark mass
Top and Higgs...
Top and Higgs...

...may be just the tip of a new particle physics iceberg!..
**supersymmetry**

<table>
<thead>
<tr>
<th>leptons</th>
<th></th>
<th>squarks</th>
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<tbody>
<tr>
<td>$e$</td>
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<td>$\tau$</td>
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<tr>
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<td>$\nu_\mu$</td>
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sparticles to match all the particles we already know!
Extra Dimensions
Time machines

Accelerators are also **Time Machines**

because they make particles last seen in the earliest moments of the universe.
Modern Colliders Create particles that existed in the universe only ~0.001 nano second after Big Bang.

100 million x Sun Temperature

“Where did all anti-matter go?”
Everything is made of electrons, up quarks and down quarks.

Everything that we can see

Need much more (x4) mass than what we see - Dark Matter *What is it?*
Searching for Dark Matter!

\[ p + X \rightarrow e^- + \mu^+ + \nu \]

\[ p + \bar{p} \rightarrow X \]

\[ X \rightarrow e^- + \mu^+ + \nu \]
Lesson of the 20th Century

The human scale of space and time is not privileged for understanding Nature, and may even be disadvantaged.
Next Energy Regime

2008 or 2009!

7 times

The energy!
Large Hadron Collider

...will be complete this year.

CERN, Geneva, Switzerland
Next energy regime

Overall view of the LHC experiments.

UC Davis

CERN, Geneva, Switzerland
Large Hadron Collider

As the Tevatron winds down...

LHC will open a new window!
LHC Experiments are very, very big!
Discoveries to come

Dark Matter

Electroweak Baryogenesis

Higgs

Particle Mass Hierarchy

Dark Energy

Grand Unified Theories

Supersymmetry

Extra Dimensions

Supersymmetric "shadow" particles
The Coming Revolutions in Particle Physics

The current Standard Model of particle physics begins to unravel when probed much beyond the range of current particle accelerators. So no matter what the Large Hadron Collider finds, it is going to take physics into new territory. By Chris Quigg

"The LHC is certain to find something new and provocative..."

of symmetry. Symmetries underlie the interactions of the Standard Model but are not always reflected in the operation of the model. Understanding why not is a key question.
A cornucopia of familiar particles spraying out from each collision will include, just occasionally, something new and wonderful.
- Sum Films
The Beginning…