Modern Physics

Thornton and Rex, Chapter 14

Elementary Particles

ELEMENTARY PARTICLES

Elementary particle physics is the science of the fundamental constituents of matter and the forces that govern their behavior.

Physicists have often used energetic beams of particles to probe into the structure of matter:-
Rutherford used radioactive sources to identify the nucleus,
Bragg (and others) used x-rays to find the electronic structure of matter.

Stable, charged high energy particles (electrons, protons) are used as probes to reach the smallest possible distance scales. The colliding of high energy particles and the analysis of the collision products is at the heart of experimental particles physics, and it is often called

HIGH ENERGY PHYSICS

FORCES

The key to understanding the properties of elementary particles is to be able to describe the forces acting between them.

Gravity: important in our everyday lives and in astronomical phenomena, but negligible for elementary particles.

Electromagnetic: when Maxwell summarized electricity and magnetism with his four laws, it became obvious that they were two aspects of the same phenomenon.

Strong: after the development of nuclear models in which all of the positively charged protons were crammed into a very small (1E-15 m) nucleus, it was necessary to postulate an attractive force acting over a short range to counteract the intense coulomb repulsion.

weak: a short-range force responsible for radioactive decays and the decays of many elementary particles.

AN EXPLOS ON OF PARTICLES

We have seen that the number of elementary particles in 1932 was 3 (the proton, the neutron and the electron).

But within the next few years many more were discovered.

The positron (the anti-electron) had been predicted by the Dirac equation. It was observed in 1932. The anti-proton was discovered in 1956.

In 1935, the Japanese physicist, Yukawa, suggested that the strong nuclear force was "mediated" by a particle that he named the π-meson (now called the pion). He expected it to have a mass intermediate to the electron (1/2 MeV) and the proton (938 MeV). It was discovered in 1947 with a mass of 140 MeV.

Estimate of the mass of the Pion

Range of nuclear force $\simeq$ 1 fm

Time to travel this distance

$$= \frac{1E-15}{3E8} \simeq 3.3E-24 \text{ s}$$

Heisenberg's Uncertainty Principle $\Rightarrow$

$$\Delta E \, \Delta t \simeq \frac{\hbar}{2} = \frac{6.58E-16}{2} \text{ eV.s}$$

$$= 3.29E-16 \text{ eV.s}$$

$$\Rightarrow \Delta E = \frac{3.29E-16}{3.3E-24} \simeq 100 \text{ MeV}$$

(or a mass, $m_\pi = 100 \frac{\text{MeV}}{c^2}$)

But only 2 years after Yukawa's proposal, a particle was discovered (in cosmic rays) by Anderson and Neddermeyer. This was thought to be Yukawa's particle, but in a brilliant series of experiments in war-time Rome in 1943, Conversi, Pancini and Piccioni showed that it couldn't be. Yukawa's particle, being the carrier of the strong force, should interact strongly with matter. But Anderson's particle was able to pass easily through dense matter. It was named the μ-meson (now called the muon) and had a mass of 106 MeV.

The pion was found in photographic plates exposed to cosmic rays on top of a peak in the Andes. Pions are created by high energy (protons) cosmic rays in the upper atmosphere. Pions decay with a lifetime of 1E-8 seconds into non-interacting muons which constitute the bulk of cosmic rays at sea-level.

Further analysis of the photographic plates showed the presence of other particles with unusual ("strange") properties:- the k-meson (kaon) and the Λ-baryon (even heavier than the proton).

In 1956, the neutrino (which had been proposed in 1930 as part of the weak nuclear force) was finally discovered.

In the 1950's, as accelerators steadily increased in energies, and as detectors became more sophisticated (visual like photographic plates, cloud chambers and bubble chambers or electronic like geiger counters or spark chambers) there were soon additional discoveries of particles with exotic names such as Σ-baryons and η-mesons.

In a few short years the number of "elementary particles" had increased dramatically and high energy physics was born.

PARTICLE CLASSIFICATION

With the proliferation of the number of these particles, much research was devoted to finding new particles, measuring their properties, and grouping them into various categories in the hope of understanding them. This classification proved to be very useful, perhaps essential, for the next step but it does involve learning a lot of new words!

All particles now known can be divided into three basic classes, the leptons, the hadrons, and the gauge (or force-carrying) particles.

Leptons: particles such as electrons, muons and neutrinos, which do not feel the strong force. leptons have spin=1/2 (in units of h).

Hadrons: particles which do participate in the strong interactions.

Gauge particles: these are the particles believed to be responsible for carrying the four known forces.

LEPTONS

There are believed to be six leptons (and six anti-leptons). They come in pairs, each consisting of one charged lepton and one neutral lepton (a neutrino). Each pair is called a generation.

generation	particle	charge	mass
1	e	-1	0.5 MeV
	ν_e	0	~ 0
2	μ	-1	106 MeV
	ν_μ	0	~ 0
3	τ	-1	1784 MeV
	ν_τ	0	~ 0

- the μ (formerly the μ-meson) is a lepton, not a meson.
- the τ was discovered at Stanford in 1976.

HADRONS

Hadrons are further subdivided into mesons and baryons.

Mesons are hadrons with integral spin (mostly 0 or 1, sometimes 2 or higher). As the name implies, most but not all, have masses between those of the electron and the proton.

Baryons are hadrons with 1/2 integral spin (mostly 1/2, but sometimes 3/2 or higher). The lightest baryons are the proton and neutron (collectively called nucleons).

GAUGE PARTICLES

These are the force-carrying particles. Each of the four basic forces is believed to involve the exchange of a particle.

Force	Particle
Electromagnetic	photon (γ)
Strong nuclear	pion (π)
Weak nuclear	Intermediate boson (W,Z)
Gravity	graviton

notes: as we will see, a more modern formulation says that the exchanged particle of the strong force is the gluon (g).
The W,Z particles were proposed by Fermi (in 1934). They were discovered at CERN in 1982.
The graviton is pure conjecture. There is no experimental evidence for its existence.

QUARKS

By the early 1960's the great number and variety of elementary particles caused Murray Gell-Mann (and others) to question the concept of "elementary". It was suggested that hadrons were made up of a small number of more fundamental particles called quarks.

Quarks are believed to have electric charges which are fractions (1/3 or 2/3) of the charge of an electron or proton. Quarks have spin 1/2. Each quark also has its corresponding anti-quark.

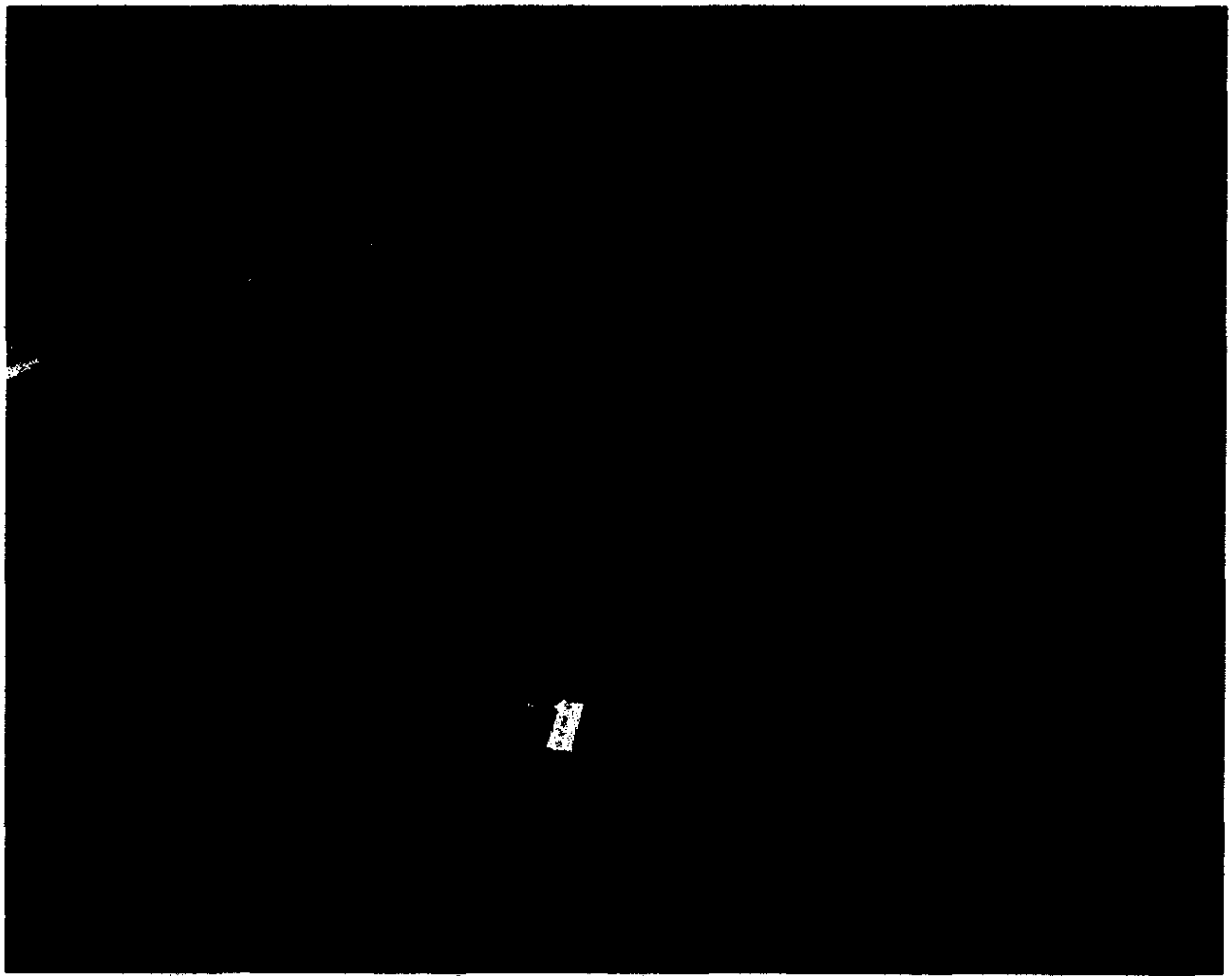
In Gell-Mann's original scheme there were only 3 kinds of quark but to explain the structure of all hadrons, the number is now up to six (arranged in three "generations" similar to leptons).

QUARK GENERATIONS

gen.	quark	charge	mass
1	up	+2/3	0.3 GeV
	down	-1/3	0.3 GeV
2	charm	+2/3	1.5 GeV
	strange	-1/3	0.5 GeV
3	top	+2/3	175 GeV
	bottom	-1/3	5.0 GeV

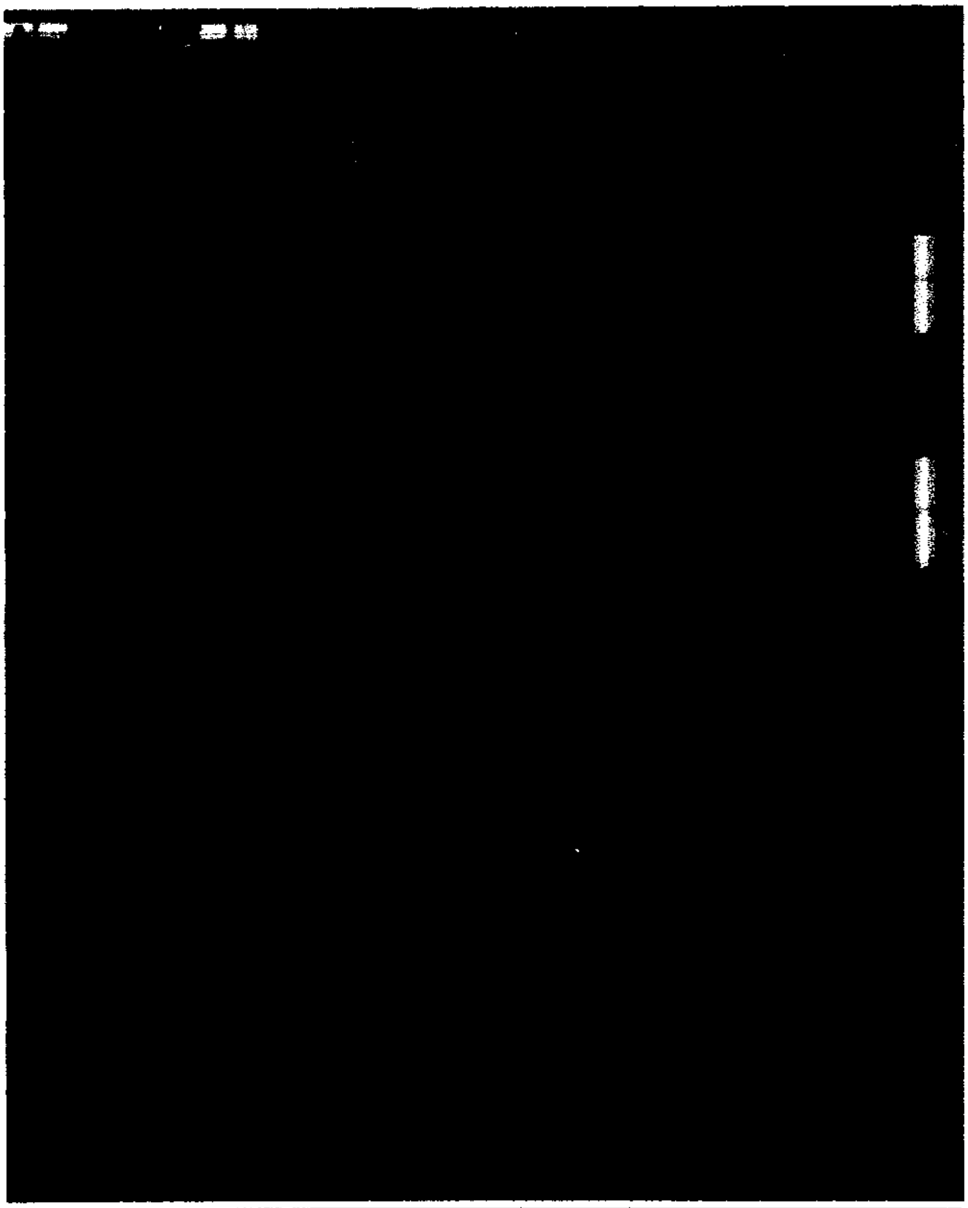
charm was discovered (by Ting and Richter) in 1974.
bottom was discovered by Lederman in 1977.
top was discovered by DØ and CDF in 1995.

The Fermilab Tevatron



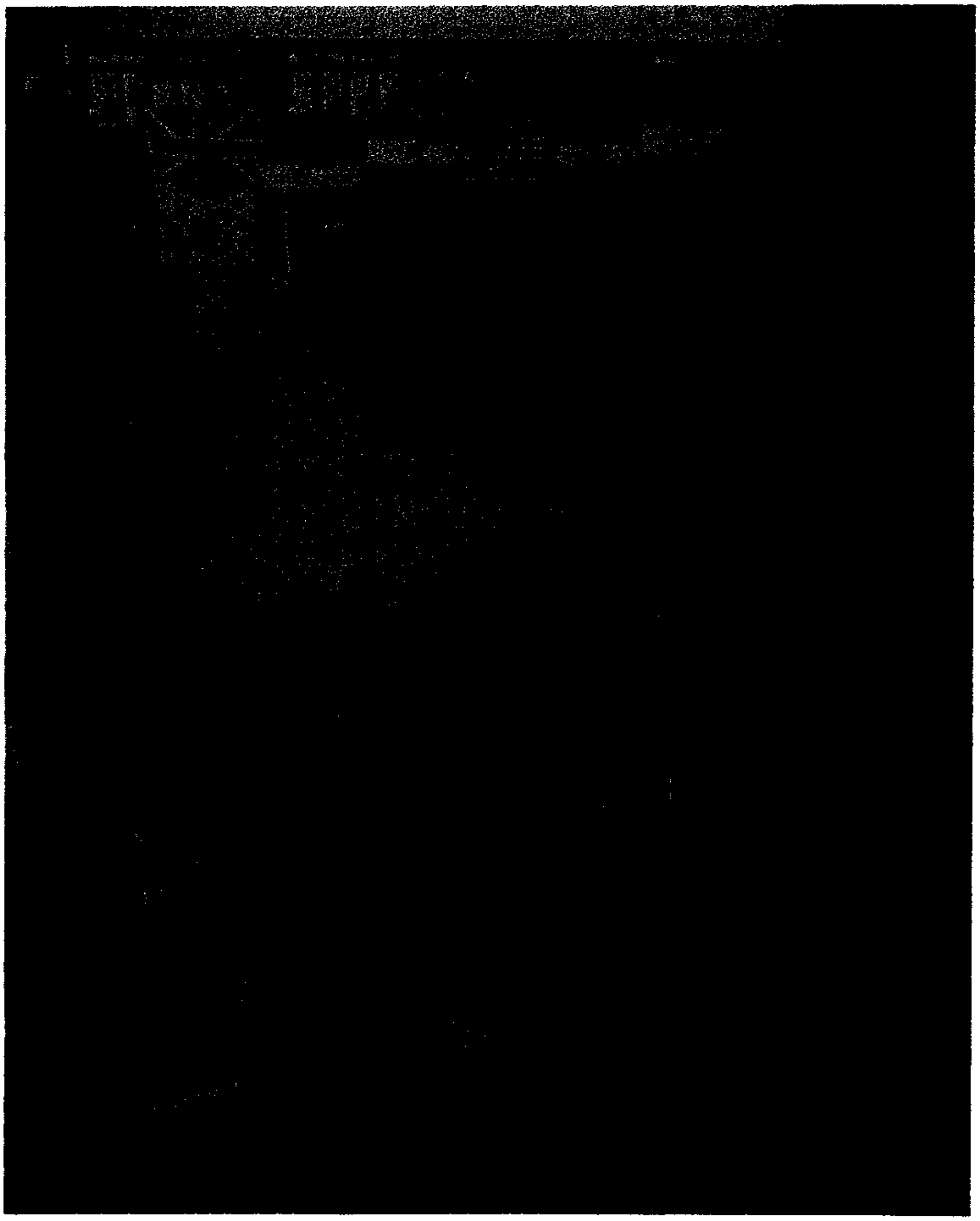
Energy = 1 TeV, circumference = 4 miles.
At 1 TeV, proton's speed is 0.9999996 c!
(1 lap takes ~ 21 μsec.)

The CDF Detector at Fermilab



Roughly a 30 foot cube, 2000 tons, 150 M$, 500 physicists.

The DØ Collaboration



Another 500 physicists!

THE QUARK STRUCTURE OF HADRONS

The quarks called strange, charm, etc. contain the quantum numbers of strangeness, charm respectively. These are arbitrary (and familiar) terms for quantities that we cannot describe but which are needed to describe the properties of particles and to express conservation laws.

According to quark theory, baryons are made up of 3 quarks, mesons are made up of a quark and an anti-quark.

Some examples:-

hadron	quark structure
proton	uud
neutron	udd
Λ^0	uds
π^+	$u\bar{d}$
π^0	$u\bar{u}$
π^-	$d\bar{u}$
k^+	$u\bar{s}$

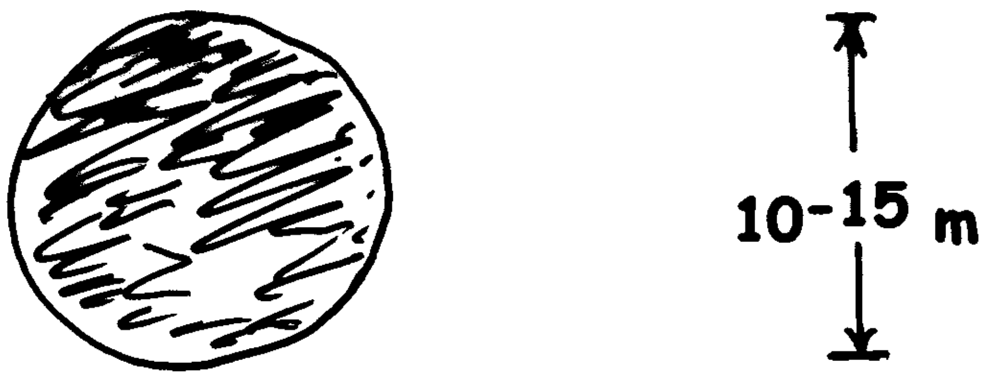
EVIDENCE FOR QUARKS

Quarks were first suggested (by Gell-Mann) as a way of drastically reducing the number of elementary particles. They successfully explained the large number of hadrons and their properties, but they were thought to be merely a mathematical device and were not physical particles.

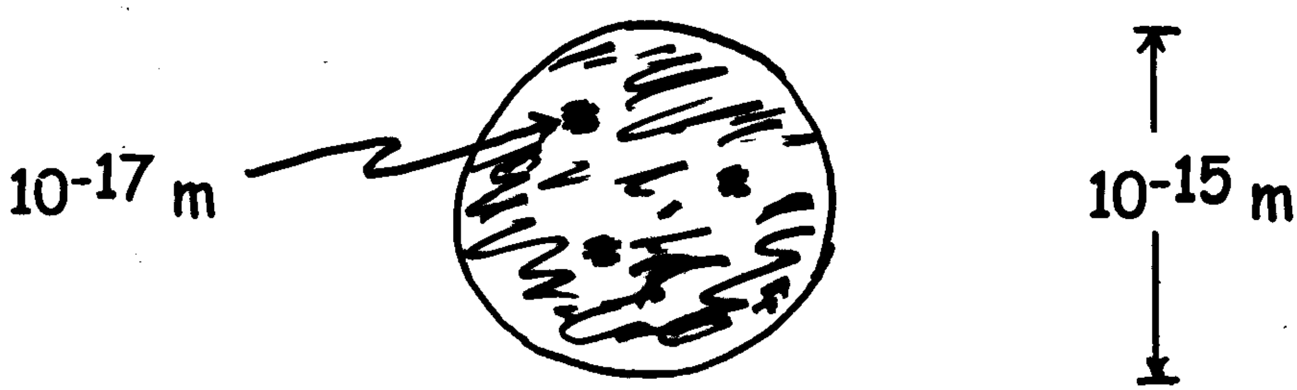
However there is now good evidence from scattering experiments that hadrons do indeed possess a structure which can be explained in terms of quarks.

ELECTRON SCATTERING

In a beautiful series of experiments in the 1950's, Robert Hofstadter (Stanford Linear Accelerator Center) scattered 300 MeV electrons off protons (and many other nuclei). His results (Rutherford-like) were consistent with the proton being a smooth, point-like, featureless sphere of size about 1E-15 meters.



In an equally beautiful experiment at SLAC in 1969 (J. Friedman, H. Kendall, R. Taylor), the electrons now had an energy of 20 GeV and the proton appeared to consist of much smaller hard scattering centers, the quarks.



PROBLEMS WITH THE QUARK HYPOTHESIS

The original quark hypothesis brought with it a number of puzzles. These seemed at first to indicate that the quark model was nothing more than a convenient mnemonic. However in pursuing and resolving these puzzles, physicists have found a dynamical basis for the quark model that promises to give a complete description of the strong interactions.

Two of the main difficulties were:-

1. quarks have not been directly observed.

2. the quark hypothesis seemed to conflict with the Pauli exclusion principle.

I'll deal with the second, first.

COLOR

In a simple quark picture a proton consists of:-

But here two identical quarks (spin 1/2) are in the same state. This is not allowed by the Pauli exclusion principle.

To comply with the Pauli exclusion principle, it is necessary to make the otherwise identical quarks distinguishable by supposing that every type of quark exists in three varieties, fancifully labeled by the colors red, green, and blue. Then each baryon can be constructed as a colorless (or white) state of a red quark, a green quark, and a blue quark.

Similarly, a meson will be a colorless quark-antiquark combination:-

($u\bar{u}$) or ($u\bar{d}$) or ($s\bar{d}$) <u>never</u> (ud)

Only colorless hadrons can be constructed from colored quarks.

QUANTUM CHROMODYNAMICS

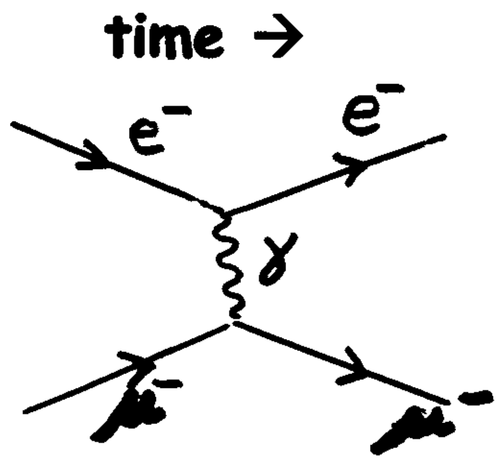
The complication of color seems a big price to pay for the trivial little concern of Pauli's exclusion principle. However, as theorists studied the question, they realized that color can explain a lot about the strong interaction including an answer to the question of why we have never seen a free quark.

QCD explains the strong force between quarks as caused by the exchange of new particles called gluons.

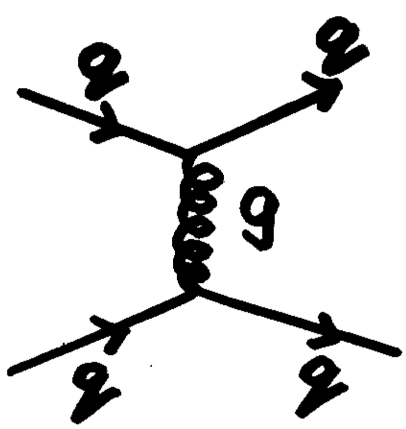
Gluons have a color-anticolor property associated with them. There are 9 types of gluons ($r\bar{r}$, $b\bar{b}$, $g\bar{g}$, $r\bar{b}$, $r\bar{g}$, $b\bar{r}$, $b\bar{g}$, $g\bar{r}$, $g\bar{b}$). When quarks interact by exchanging a gluon, they exchange color. Because gluons are colored, they interact among themselves. As the separation between two quarks increases, the force of attraction increases. Thus an infinite amount of energy would be needed to separate two quarks. This is why we will never see a free quark. This is the concept of confinement.

FEYNMAN DIAGRAMS

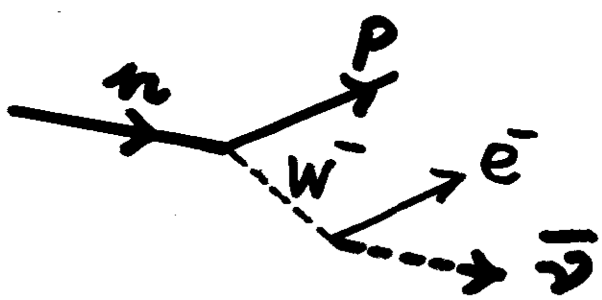
The interaction between two particles can be represented in a shorthand sketch that shows the process and, together with some simple rules (developed by Richard Feynman), enable rates or probabilities to be calculated.



electron - muon scattering (via photon)



quark - quark scattering (via gluon)



neutron decay (via W)

ELECTROWEAK THEORY

The present theory of high energy physics is called The Standard Model. It consists of two parts:-

QCD which applies to the strong force

and

the Electroweak theory which applies to the weak and electromagnetic forces.

The theory of weak interactions (Fermi, 1933) was very similar to Quantum Electrodynamics (QED), the theory of electromagnetism incorporating quantum theory and (eventually) relativity. In the 1960's Weinberg, Glashow and Salam developed a "unified" theory which related the two forces. The difference between the forces was that em required a massless photon (γ) while the weak force required massive force carriers ($W^{\pm}$, Z^{0}). These new particles were eventually discovered at CERN by Carlo Rubbia and Simon van der Meer. $m_{W^{\pm}}$ = 80 GeV, $m_{Z^{0}}$ = 90 GeV.

THE HIGGS BOSON

Why do 3 families of particles exist, and why do their masses differ so dramatically?

In the standard model of particle physics, we believe that "empty" space is filled with a field that gives quarks and leptons their mass. This field is called the Higgs field (named for Peter Higgs, a professor at Edinburgh University in Scotland).

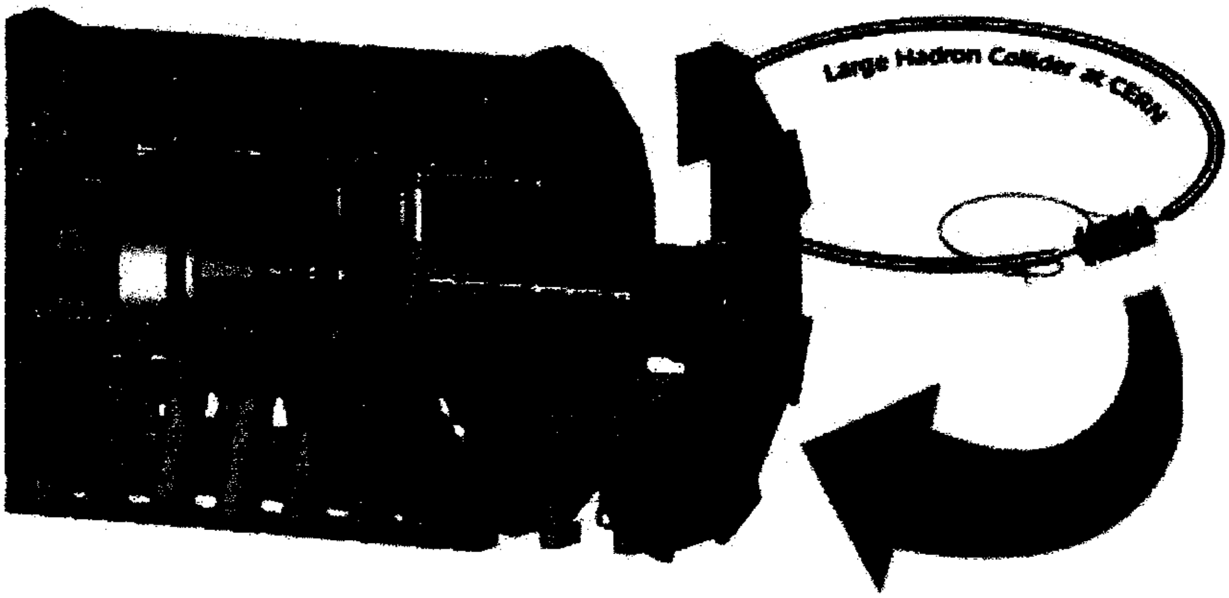
A mass-generating particle, the Higgs Boson, is also predicted. This is presently being searched for at Fermilab by the collider experiments, CDF and DØ.

We have a short time window in which to discover the Higgs particle. Next year (summer?) the Large Hadron Collider, a new accelerator at CERN, will start to operate. The LHC will have 7 times the energy and, eventually, 100 times the luminosity (collision rate).

CERN

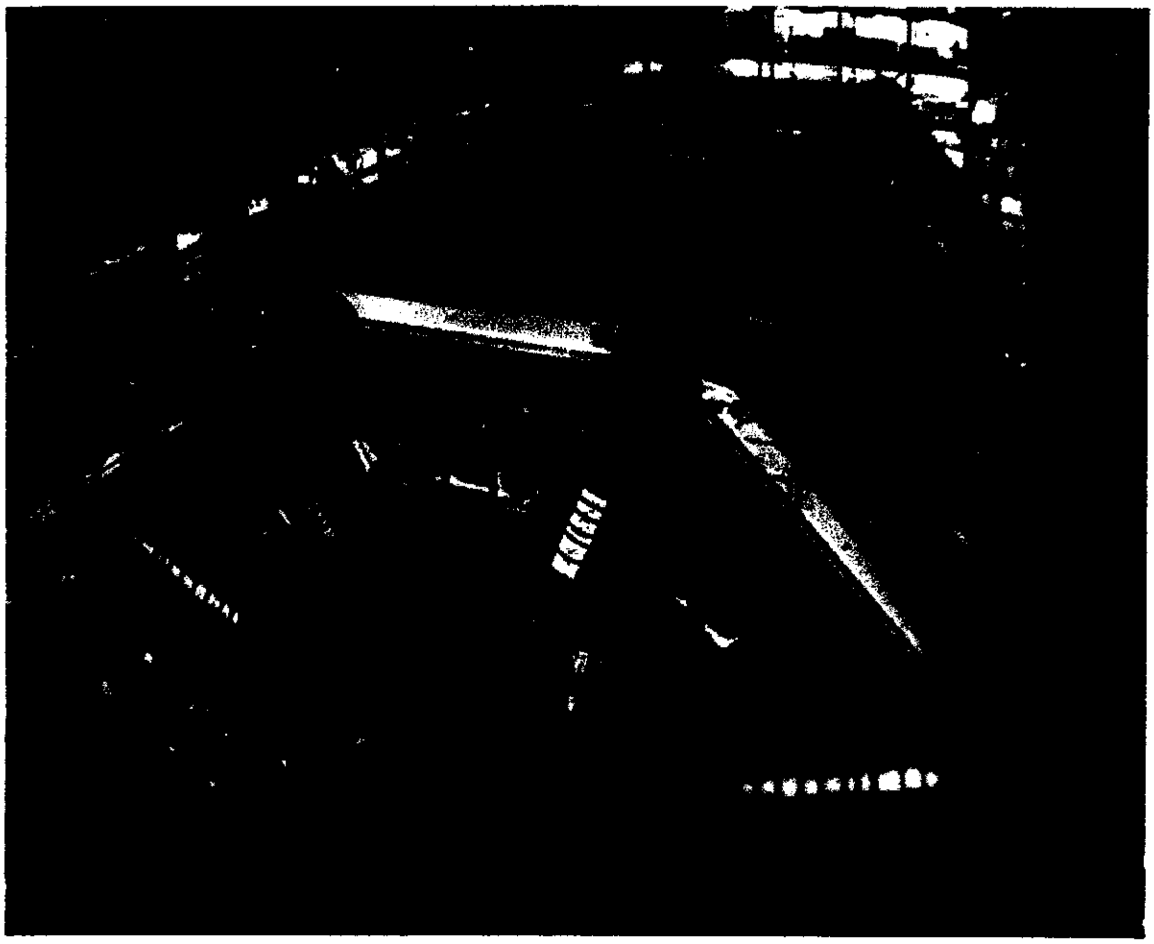
Geneva, Switzerland

The ATLAS Detector

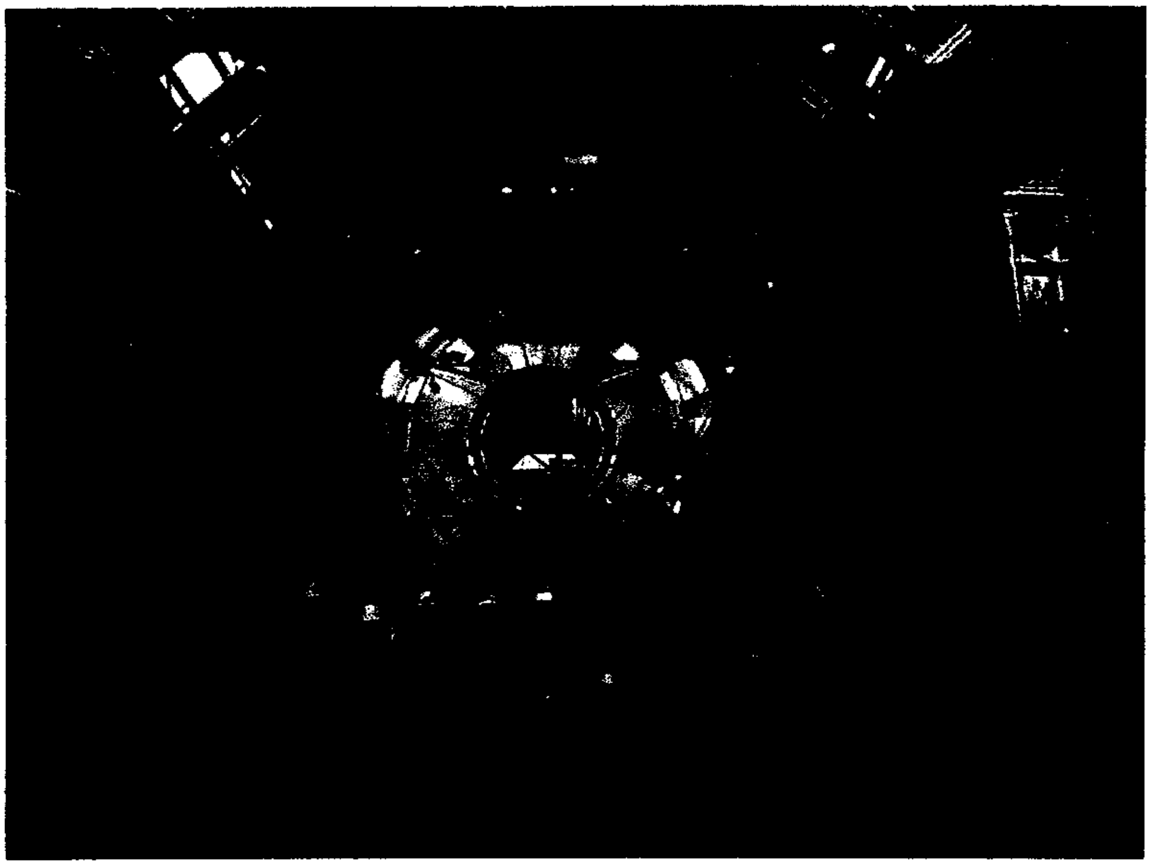


The large hadron collider is a 17-mile in circumference accelerator under the Swiss-French border.

ATLAS is a 70 foot cube, approx 500 M$, 10,000 ton detector, with ~2000 physicists.



The first photo shows the coils of the huge superconducting toroidal magnet (there are 8 coils in total). The yellow cherry-picker gives an idea of the scale of the project.



The second photo shows the team responsible for inserting the calorimeter system inside the magnet. The central calorimeter, weighing approximately 2000 tons, is the silvery object behind the group. Many of the calorimeter modules were built and assembled at MSU.

GRAND UNIFIED THEORIES

The successful search for the intermediate bosons ($W^{\pm}$, Z^{0}) shows the unification of the weak and electromagnetic interactions.

In recent years, physicists have been working on grand unified theories (GUTs) in an attempt to unit the electroweak force with the strong nuclear force.

If these grand unified theories should work out, the last remaining step would be to include the gravitational force. (Albert Einstein devoted the last 35 years of his life to developing a unified theory of the EM and gravitational fields and, of course, died without accomplishing this goal.)

It is now believed that, at the high temperatures of the Big Bang, all four forces appeared in exactly the same symmetrical form. As the universe cooled off, however, the four forces and their related gauge particles became distinct. Theoreticians refer to this as <u>symmetry breaking</u>.

This cosmological connection implies that we may need to understand the origin of the universe better before we can understand the elementary particles.

Or perhaps we can use our increased knowledge of elementary particles to cast an additional light on how our universe began. For example, we have recently realized that neutrinos have a (very tiny) mass. Since neutrinos are the most numerous particle in the universe, even a tiny mass will have a significant effect on the evolution of the universe.

In either case, it is clear that a trend towards unification (from the very large to the very small) pervades physics today.

It certainly leads to the last topic of Cosmology (chapter 16) which we won't get to, but I'll put my slides on the web.