

Lecture 2a: Lightning History

What were some of the major historical developments over the last century or so?

What are some of the basic qualitative properties of the various particles and forces?

Nuclear forces (radioactivity)

In 1896 Henri Becquerel accidentally exposed photographic plates to uranium.

In 1898 Marie and Pierre Curie isolated polonium and radium (much stronger sources).



The electron

In 1897 J.J. Thomson studied “cathode rays” emitted by a hot electrode. Measured deflection by B and E fields.

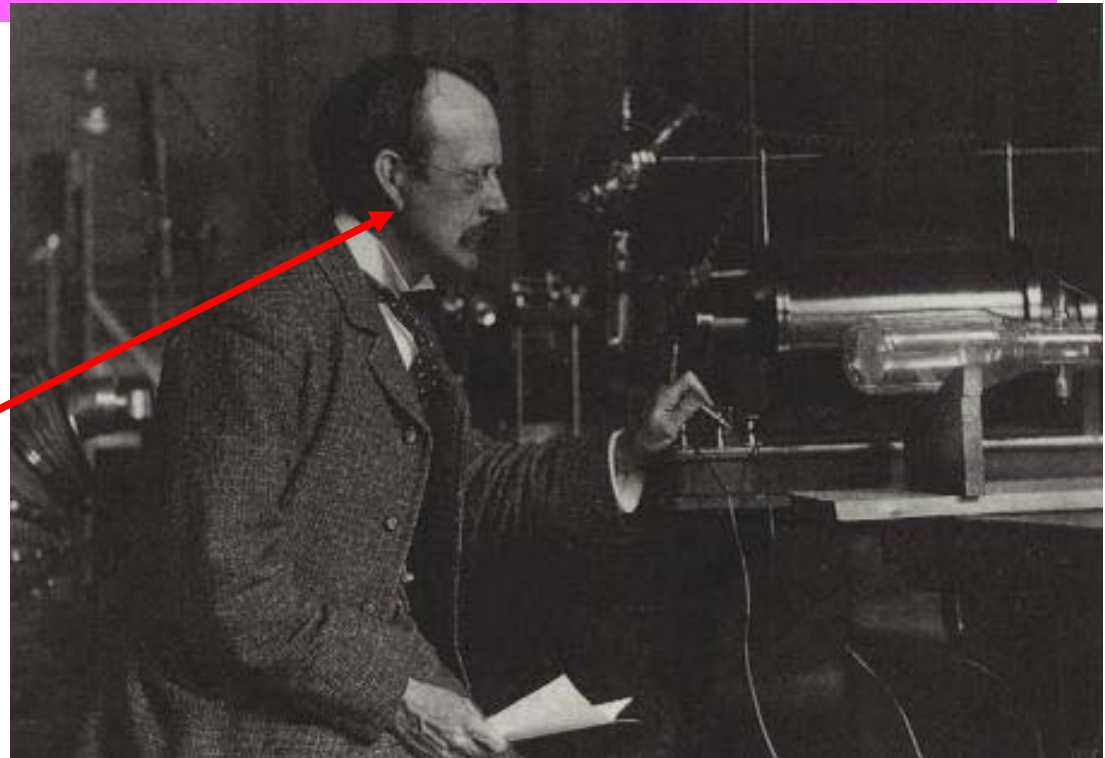
$$F_E = q E, \quad F_B = q v \times B.$$

Computed velocity $v = E/B$ using crossed fields, then

$q/m = v/(B r_{\text{curv}})$ using B alone.

Found very large q/m .
Inferred small m_e .

Note sophisticated
photon detector



The photon

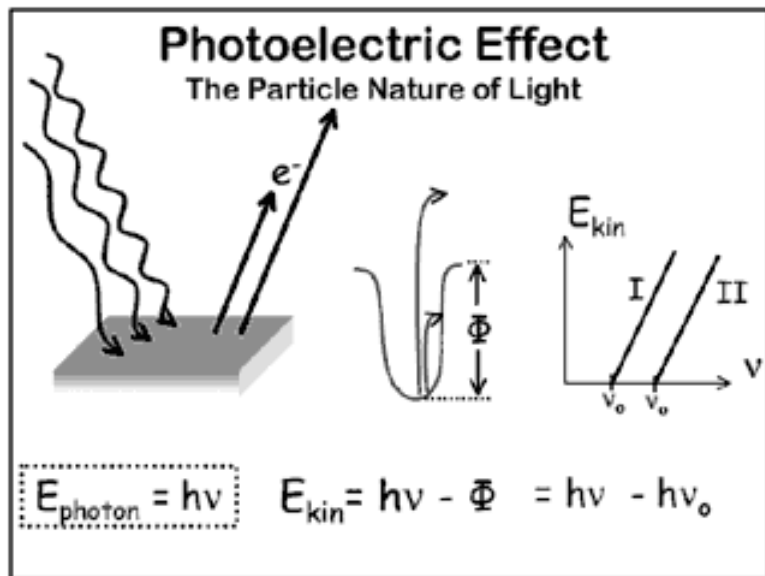
Light is a particle:

In 1905 Einstein interpreted the photoelectric effect as electron emission due to absorption of a quantum of light:

$$E_e = h \nu - \Phi.$$

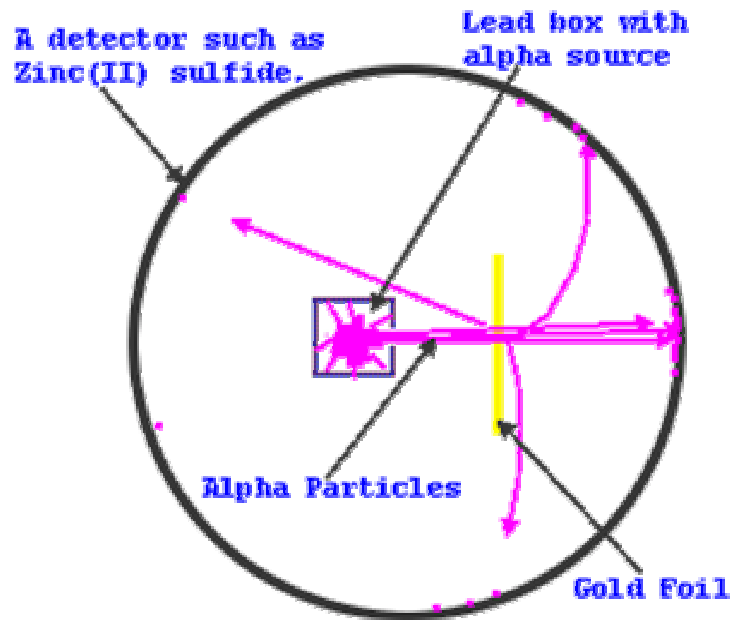
Increasing the light intensity does **not** increase E_e .

Confirmed by Millikan (1916), Compton (1923).



The nucleus

In 1909 Rutherford scattered alpha particles (He nuclei) off a gold foil. One in 8000 scattered at a large angle.



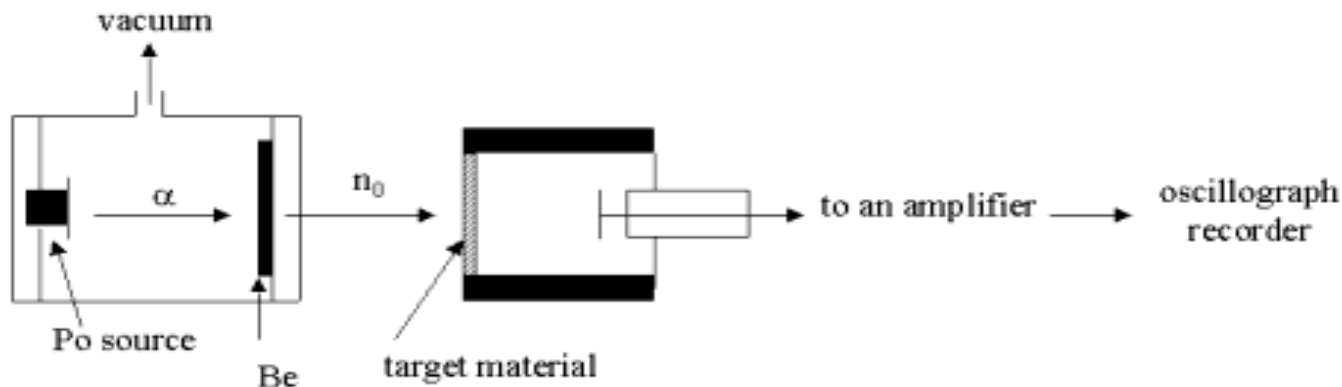
“as if you fired a 15-inch naval shell at a piece of tissue paper and the shell came right back and hit you”

Evidence that the positive charge in an atom is in a tiny core.

The neutron

Why did helium have twice the charge of hydrogen, but four times the mass? $\text{He} = 4 \text{ p} + 2 \text{ e}$ was proposed.

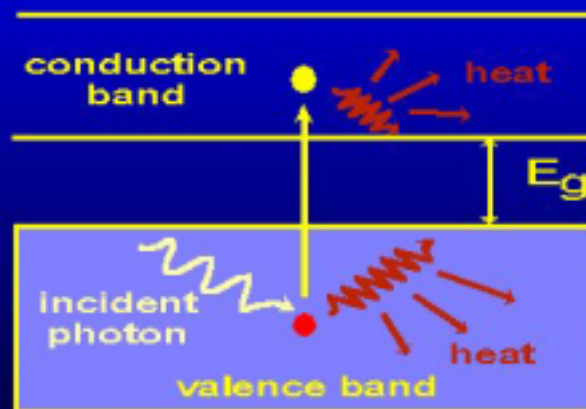
In 1928, W. Bothe and H. Becker found that α particles from Po cause Be to emit a penetrating radiation, first thought to be photons (γ rays). James Chadwick studied ejection of protons from various elements, showed that the neutral particle (n) had a mass very close to m_p .



The positron

In 1927, P.A.M. Dirac invented a relativistic wave equation for the electron, containing solutions with $E = +(p^2c^2 + m^2c^4)^{1/2}$ and $E = -(p^2c^2 + m^2c^4)^{1/2}$. He interpreted the latter as “filled states”, the “Dirac sea”. Excitations would have opposite charge but the same mass as electrons. $E_g = 2 m_e c^2 = 1.2 \text{ MeV}$ in this case.

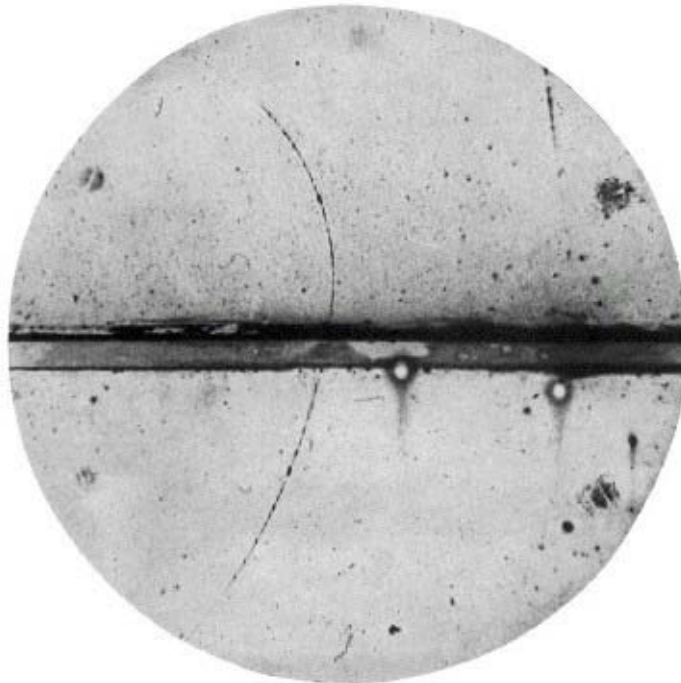
The generation of electron-hole pairs by light



The positron discovered

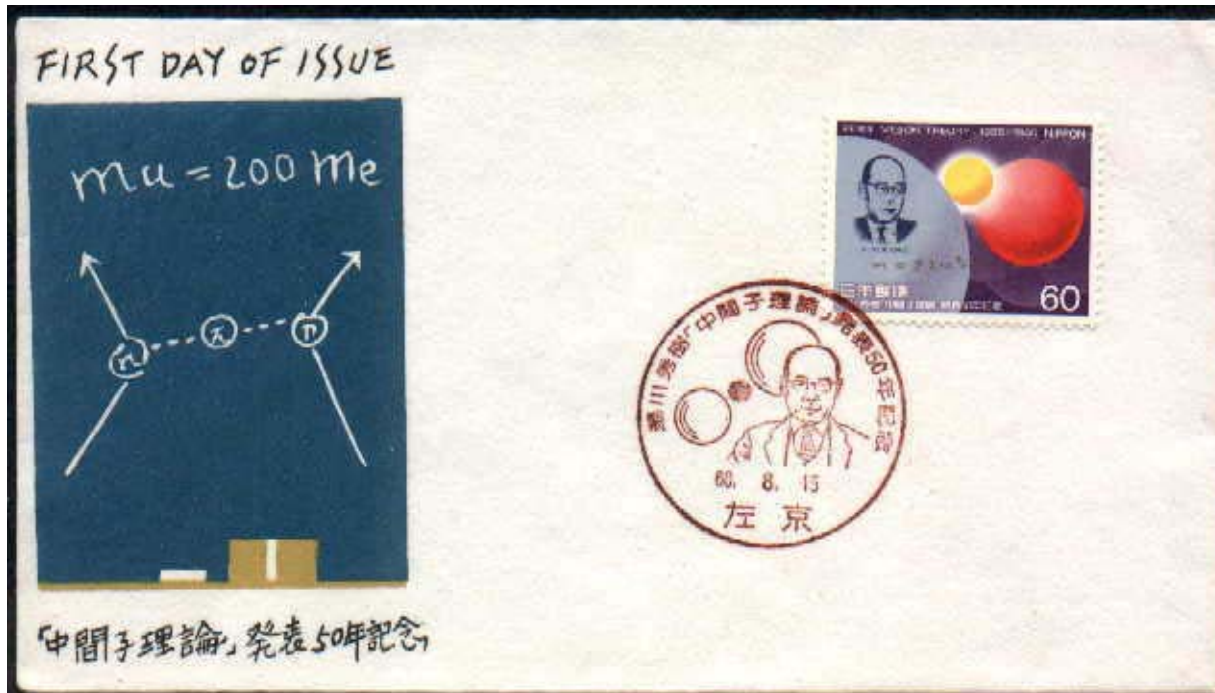
Era of using cosmic rays for fundamental discoveries begins.

In 1932 Carl Anderson found a cosmic ray particle with positive charge and mass close to that of the electron. Direction inferred from energy loss across lead plate -> more curvature in B field.



What binds the nucleus?

In 1934 H. Yukawa proposed a new particle, a **meson**, to carry the strong force between neutrons and protons. Range of force led to prediction of $m_{\text{meson}} = 200 m_e$, "middleweight" between m_e and $m_p = 1837 m_e$



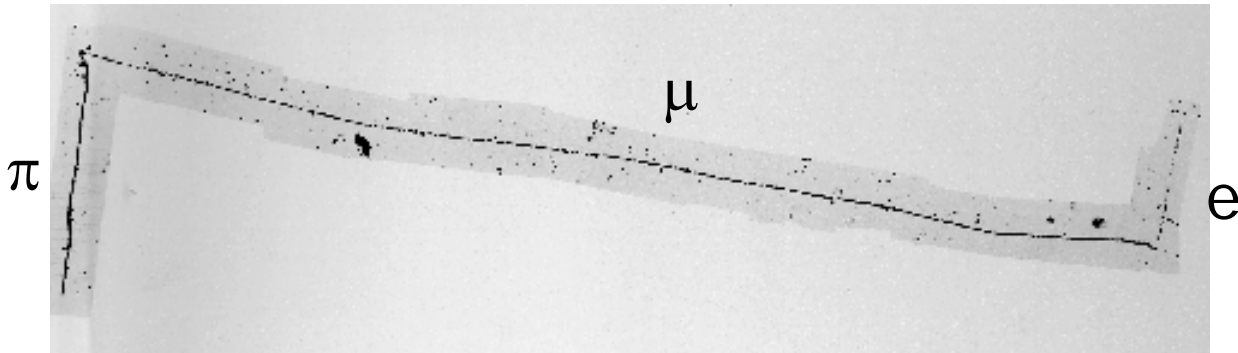
Which meson is it?

In 1937 cosmic rays with about the right mass were found. But in 1946 it was shown that the **bulk** of these interact too weakly with nuclei to be Yukawa's meson.

These are **muons** (μ). They only feel the electromagnetic and weak interactions, and decay via $\mu \rightarrow e + \bar{\nu}_e + \nu_\mu$
With lifetime $\tau_\mu = 2 \times 10^{-6}$ sec.

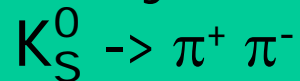
In 1947 C.F. Powell et al. found the **pion** (π) in cosmic rays at high altitudes ($\tau_\pi = 3 \times 10^{-8}$ sec).

$\pi \rightarrow \mu \rightarrow e$ decay chain seen. π **was** Yukawa's meson.

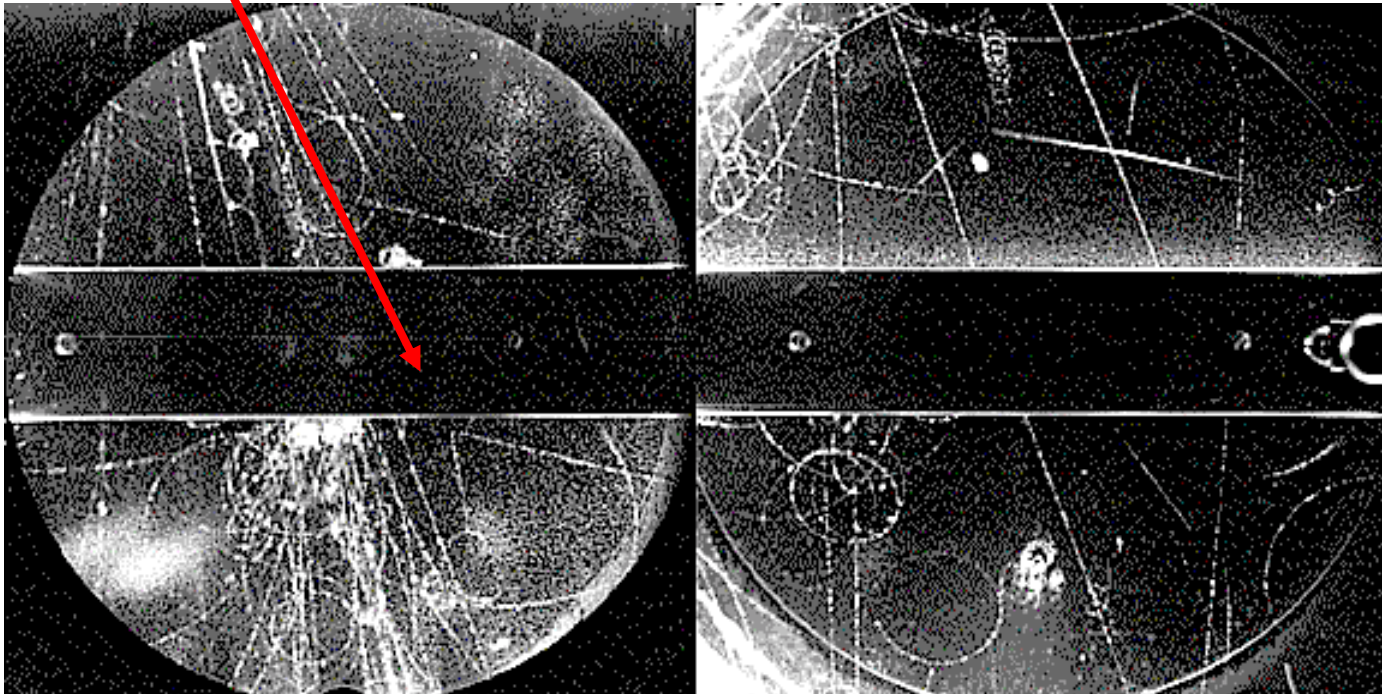
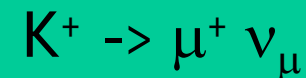


Strange particles

Later in 1947, C. Butler and G. Rochester discovered two new hadrons (strongly interacting particles) in cosmic rays, the **kaons**:



and



What's strange about them?

Era of using particle accelerators for fundamental discoveries begins.

In 1952 Brookhaven Cosmotron produces strange particles in **pairs**.

Produced **strongly** (large probability) but decay **weakly** (long lifetime).

Also strange **baryons** (decay into p or n), such as

$\Lambda^0 \rightarrow p^+ \pi^-$. $m_\Lambda = 1110 \text{ MeV} > m_{p,n} = 940 \text{ MeV}$.

$\pi^- p^+ \rightarrow K^0 \Lambda^0$ $\pi^- p^+ \rightarrow K^+ \Sigma^-$ $\pi^- p^+ \rightarrow K^0 \Sigma^0$

$\pi^- p^+ \not\rightarrow K^0 n$ $\pi^- p^+ \not\rightarrow \pi^+ \Sigma^-$

Notion of **strangeness conservation**

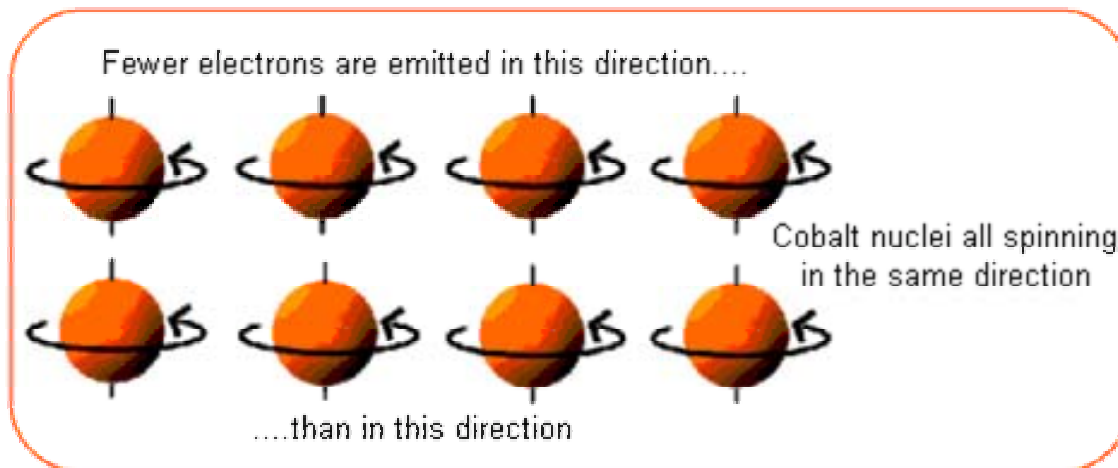
- like electric charge conservation,

but **violated** by the weak interactions.

Parity violation

In 1956 the K^+ was actually thought to be 2 particles
 $\theta^+ \rightarrow \pi^+ \pi^0$ ($P = +1$) and $\tau^+ \rightarrow \pi^+ \pi^0 \pi^0$ ($P = -1$)

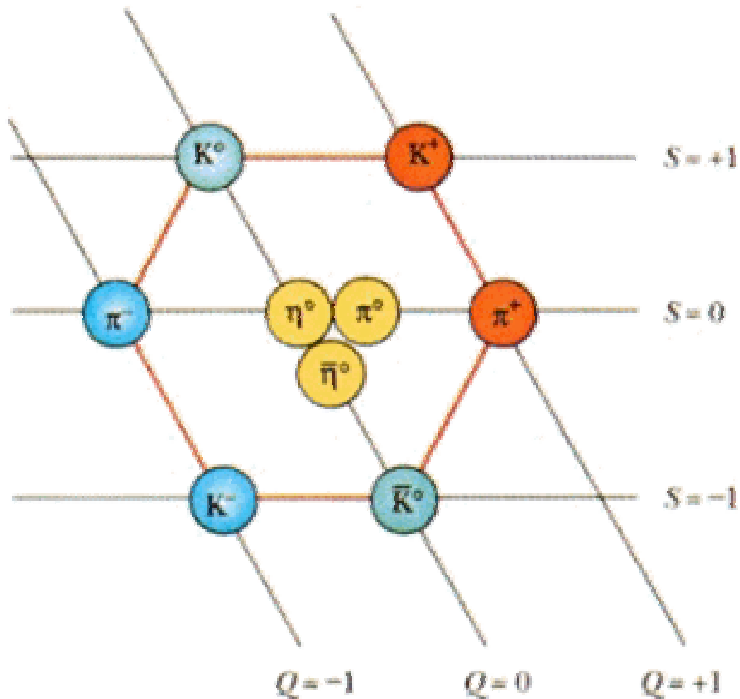
T.D. Lee and C.N. Yang resolved the τ - θ puzzle by proposing that **parity is violated** in the weak interactions. Quickly confirmed by C.S. Wu using e^- direction in beta decay of polarized ^{60}Co .



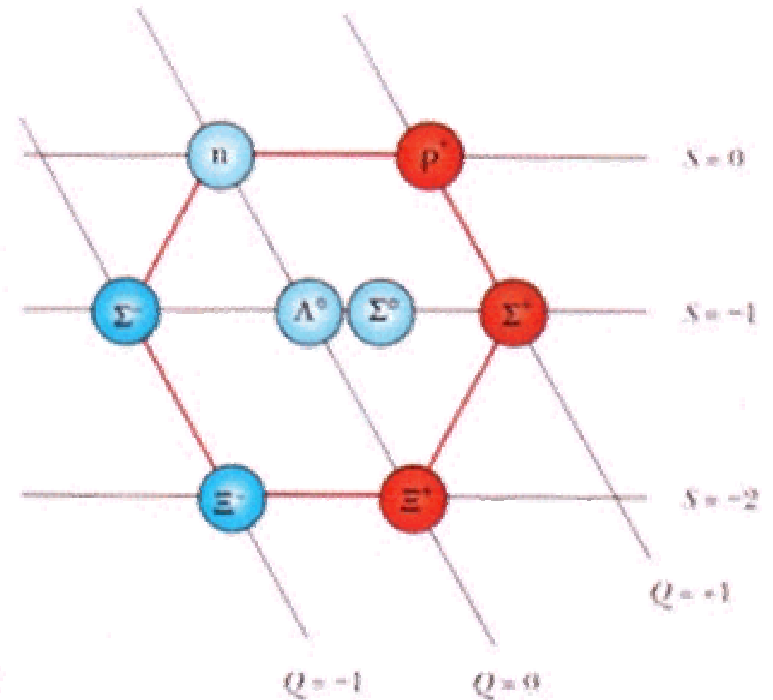
Some order to the chaos

In 1961 M. Gell-Mann introduces "The Eightfold Way" to organize the hadrons. Predicts the Ω^- ($S = -3$).

mesons

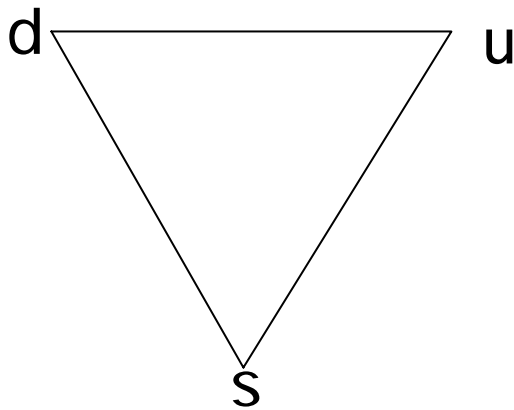


baryons

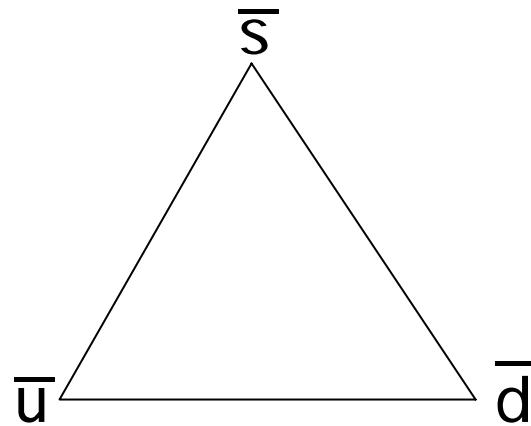


The quark model

In 1964 Gell-Mann and Zweig introduce quarks (aces) to explain success of "The Eightfold Way".



quarks



antiquarks

$$Q_u = 2/3, \quad Q_d = Q_s = -1/3$$

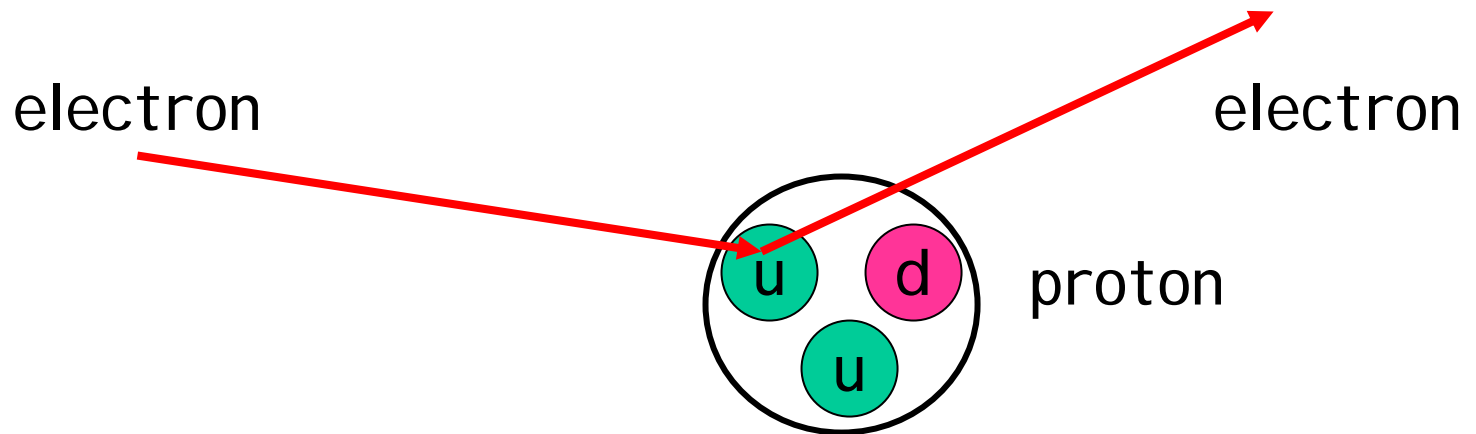
$$S_u = S_d = 0, \quad S_s = -1$$

Mesons are $q\bar{q}$ pairs; baryons are qqq triplets.

Are quarks real, or a mathematical mnemonic?

Quarks are real

In late 1960s SLAC repeats the Rutherford scattering experiment at ~10000 times the original energy. Sees "Bjorken scaling" in "deep inelastic scattering": Quarks are "asymptotically free" when probed at very short distances, even though they are bound tightly at long distances (Gross, Politzer, Wilczek, 1973).



CP violation

The weak interactions were known to violate P and C (charge conjugation). But the product CP was thought to be a good symmetry. The two neutral kaons, K_L and K_S , were assigned opposite CP, based on

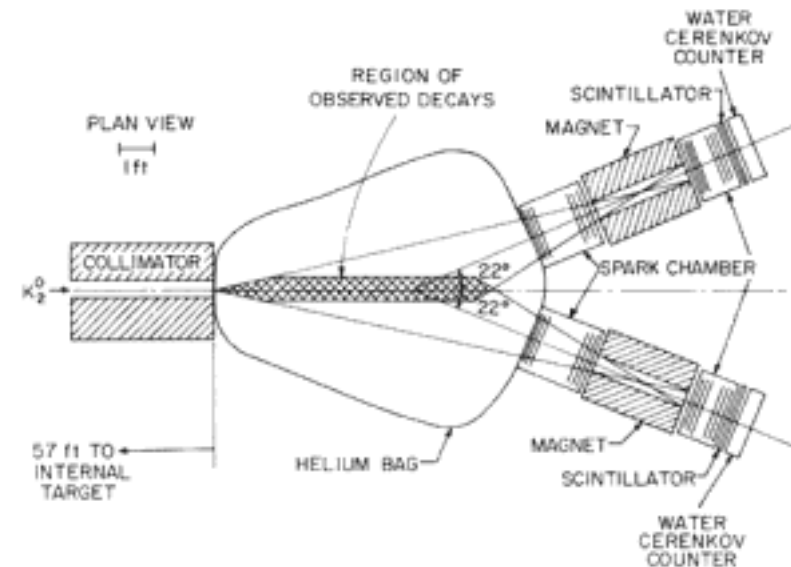
$$K_S \rightarrow \pi^+ \pi^-$$

$$K_L \rightarrow \pi^+ \pi^- \pi^0$$

In 1964 Christenson, Cronin, Fitch and Turlay used a K_L beam at Brookhaven to discover

$$K_L \rightarrow \pi^+ \pi^-$$

hence CP violation.
Mystery for many years,
still not well tested.



Weak neutral currents

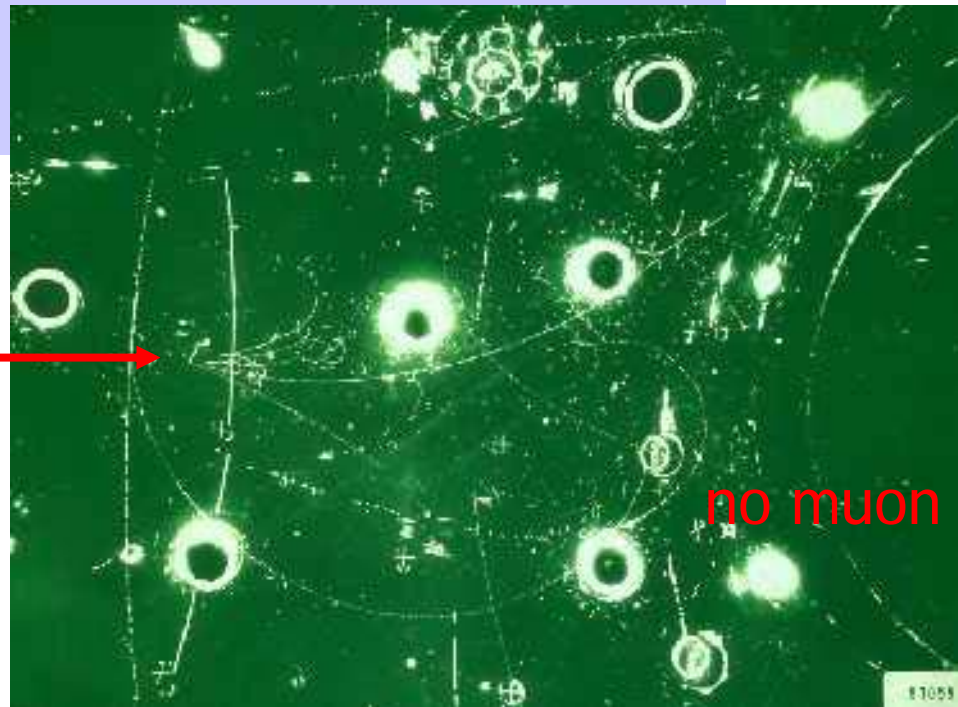
In the 1960s theories were developed by Glashow, Weinberg and Salam which unified the weak and electromagnetic interactions, but predicted a new, neutral, weak boson, the Z^0 .

First experimental tests came in neutrino scattering experiments at CERN in 1973 (X = "anything")

W^+ exchange: $\nu_\mu p \rightarrow \mu^- X$

Z^0 exchange: $\nu_\mu p \rightarrow \nu_\mu X$

neutrino beam



no muon

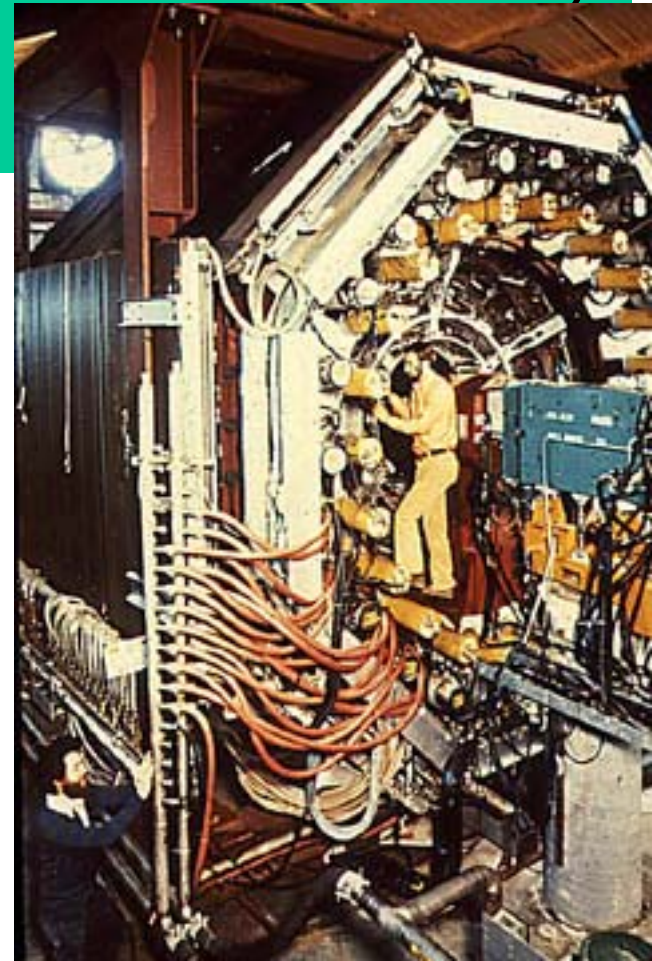
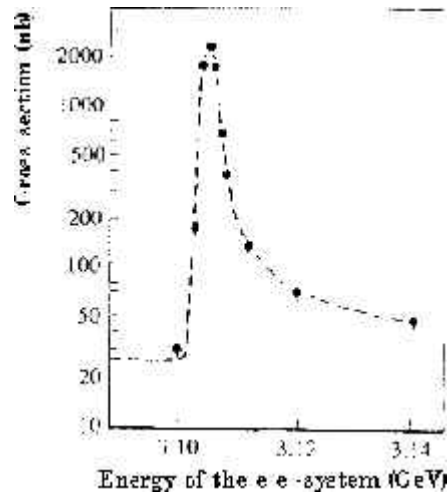
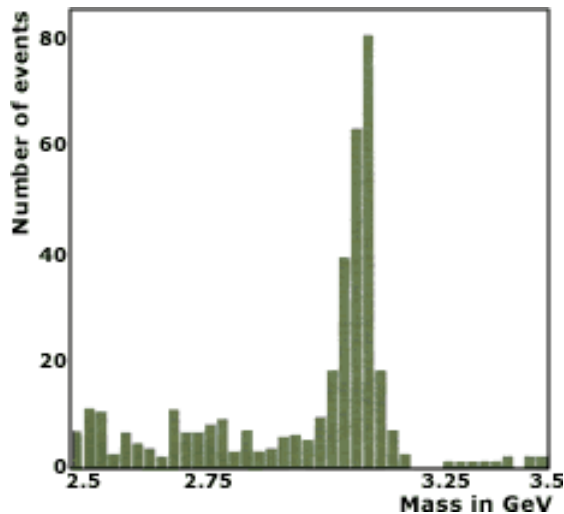
The November Revolution

Era of fundamental discoveries with colliding beams begins.

New, heavy hadron ($m = 3.1 \text{ GeV}$) discovered simultaneously at Brookhaven (J) and SLAC (ψ). $c\bar{c}$ bound state. Others soon followed.

$$p + \text{Be} \rightarrow J + X \rightarrow e^+e^-X$$

$$e^+e^- \rightarrow \psi \rightarrow X$$



The third generation

When the muon was discovered, I.I. Rabi was said to have uttered, "Who ordered that?"

By late 1974, electrons, muons, neutrinos and quarks could be fit into a nice pattern, with 2 "generations".

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

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

However, in 1975, at the same detector where the ψ was discovered, a new lepton appeared, the τ . First member of 3rd generation.

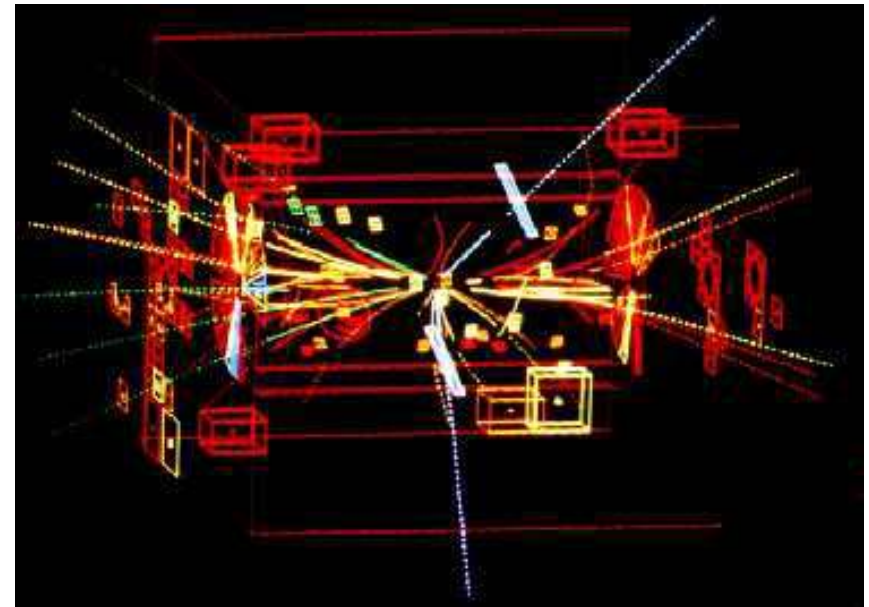
$$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

Weak Bosons Detected

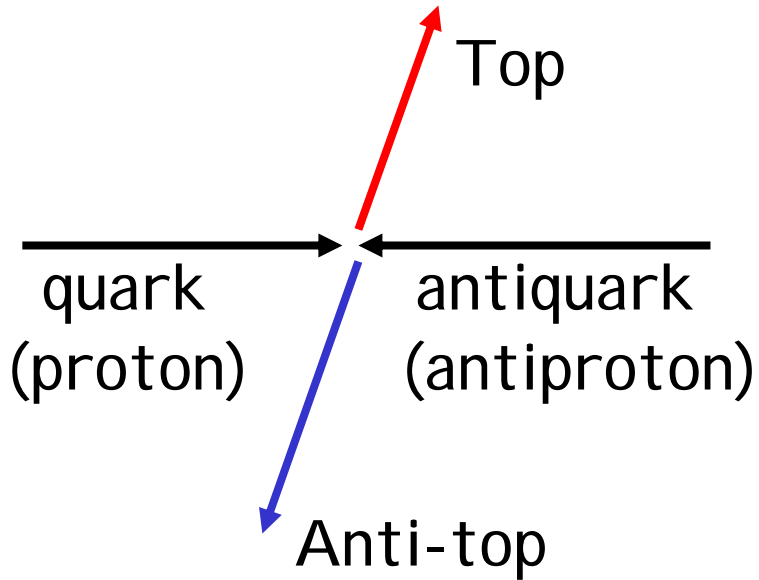
Masses of W and Z bosons could be estimated at 80, 90 GeV, from weak neutral current data. Far heavier than any particle produced to date.

CERN builds the Sp \bar{p} S, p (270 GeV) + \bar{p} (270 GeV), UA1, UA2 detectors observe W , Z decays to leptons.

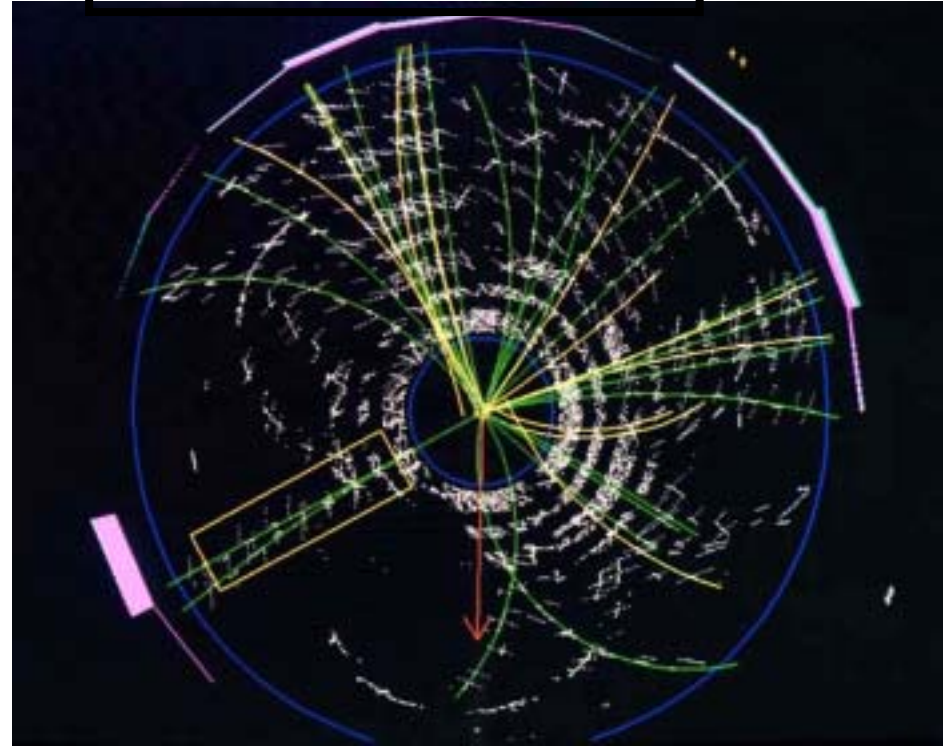


Discovery of the Top Quark

At Fermilab Tevatron



Top Quark Event



Completed the 3rd generation.