WEAK INTERACTIONS

- FIRST FORCE DISCOVERED IN NON-CLASSICAL TIMES

  BECQUEREL – 1896

- STUDY OF WEAK INTERACTIONS CONTINUAL SOURCE OF DISCOVERY
  - CONTINUOUS β SPECTRUM $\rightarrow \nu$
  - PARITY VIOLATION
  - CP VIOLATION
  - MASSIVE GAUGE BOSONS
    - $\hookrightarrow$ SPONTANEOUS SYMMETRY BREAKING
  - FIRST EXTENSION OF RENORMALIZABLE GAUGE THEORY APPROACH
  - UNIFICATION OF GAUGE FORCES

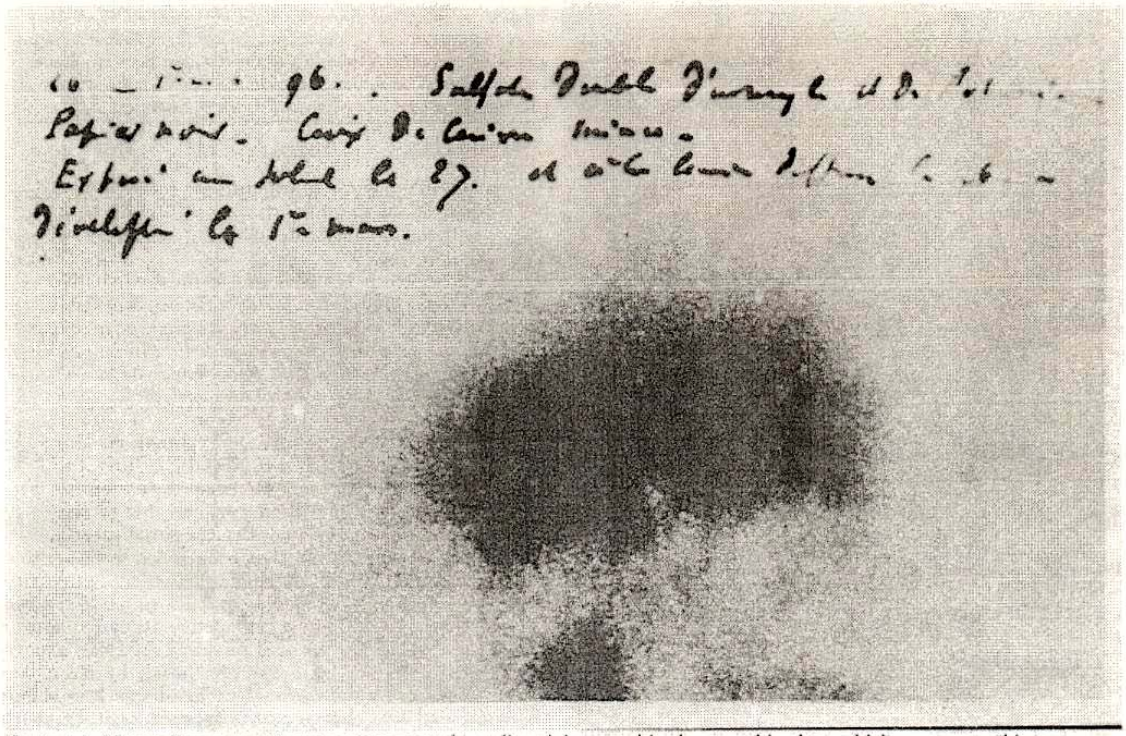


FIGURE 1. HENRI BECQUEREL'S FIRST EVIDENCE for radioactivity was this photographic plate, which was wrapped in opaque black paper and placed under a piece of uranium salt on 26 February 1896.

> and there left for another opportunity of insolation. But the sun persistently kept behind clouds for several days, and, tired of waiting (or with the unconscious prevision of genius), Becquerel developed the plate. To his astonishment, instead of a blank, as expected, the plate had darkened under the uranium as strongly as if the uranium had been previously exposed to sunlight, the image of the copper cross shining out white against the black background.[2]

Becquerel observed the same effect with several uranium salts, from which he inferred that the effect was due to the presence of uranium. He confirmed this by an experiment in which he used only pure uranium metal and obtained the same result. He concluded that uranium was emitting a form of radiation that could both penetrate opaque paper and expose a photographic plate. Subsequent experiments, by the Curies and others, showed that other substances, including the newly discovered elements radium and polonium, emitted similar radiation. What that radiation actually was, however, remained an unanswered question.

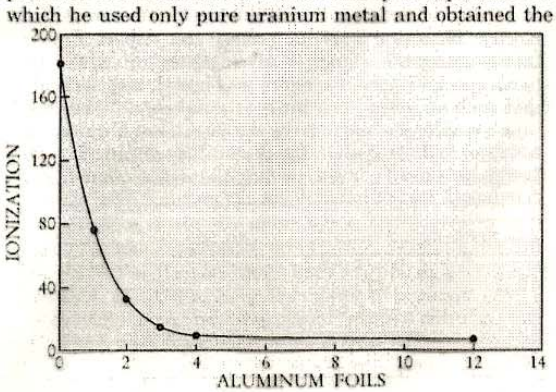


FIGURE 2. RUTHERFORD'S 1899 MEASUREMENT (redrawn) of the ionization produced in his detector by the radiation from a uranium source, as a function of the number of absorbing aluminum foils covering the source. The rapid decrease up to four foils is due to the absorption of α particles. But the long tail is due to the penetrating β radiation, which was only slightly attenuated by the additional foils.

The alphabet: α, β, γ

The first step in deciphering the nature of the radiation emitted by uranium was taken by Ernest Rutherford in 1899. He measured the intensity of the emitted radiation as a function of the thickness of aluminum foils placed over the uranium. He found that, at first, each additional plate reduced the amount of radiation by the same, constant fraction, but that beyond a certain thickness the intensity of the radiation was only slightly reduced by adding more layers. (See figure 2.) Rutherford concluded: "These experiments show that the uranium radiation is complex, and that there are present at least two distinct

TYPICAL PROCESSES

$n \to p e^- \bar{\nu}_e$ $\quad 10^3\,s$

$\nu_e p \to n e^+$

$\Lambda \to p \pi^-$ $\quad 10^{-10}\,s$

$\pi^+ \to \mu^+ \nu_\mu$ $\quad 10^{-8}\,s$

$\mu^+ \to e^- \bar{\nu}_e \nu_\mu$ $\quad 10^{-6}\,s$

- LIFETIMES LONG cf

  ELECTROMAGNETIC $\sim 10^{-19}\,s$
  "STRONG" $\sim 10^{-23}\,s$

- DO NOT ALWAYS INVOLVE ν

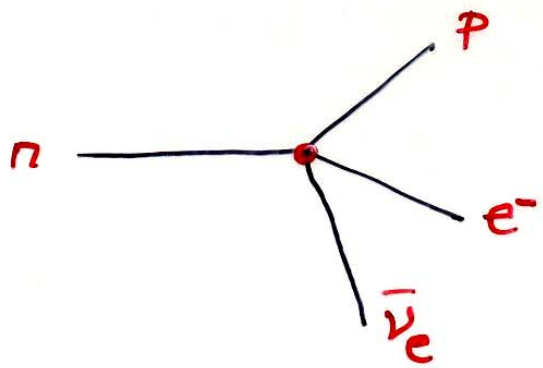
- DECAY LIFETIMES DEPEND ON:

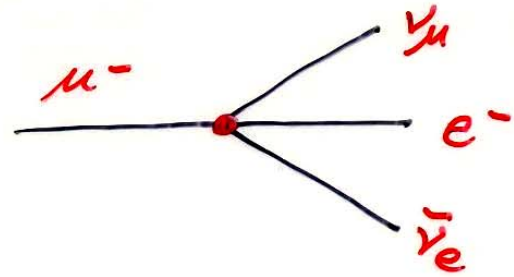
  PHASE SPACE $\times\ \mathcal{M}_{WEAK}$

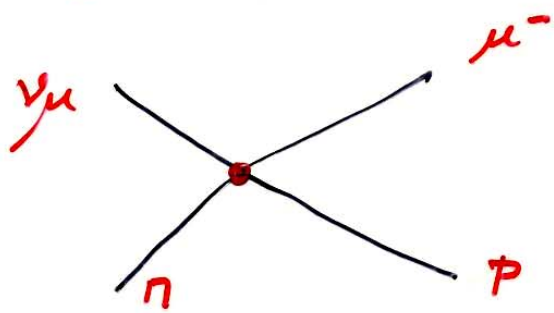
- LEPTON FLAVOUR CONSERVATION

PHENOMENOLOGICAL "THEORY"

DUE TO FERMI – 4 FERMIONS COUPLE AT POINT IN SPACE TIME

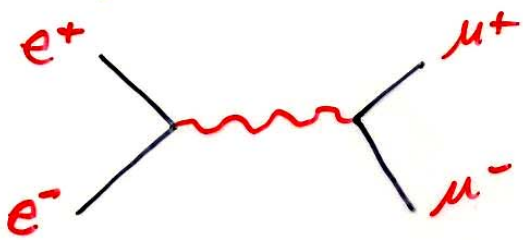






FERMI CONSTRUCTED LAGRANGIAN

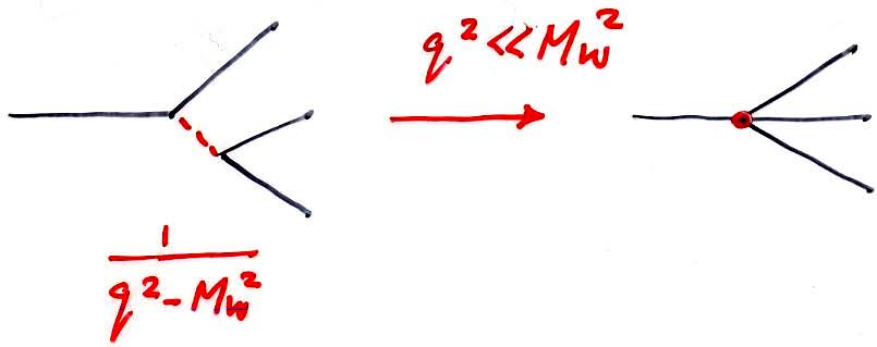
cf. ELECTROMAGNETISM



$$\mathcal{M} = \bar{u}\, ie\gamma^\mu u \, \frac{g_{\mu\nu}}{q^2} \, \bar{v}\, ie\gamma^\nu v \qquad \sim \frac{\alpha}{q^2}$$

- ELECTROMAGNETISM $\gamma^{\nu\mu} \rightarrow$ VECTOR
- WEAK INTERACTION $\rightarrow$ GUESS FORM OF INTERACTION AND COMPARE WITH EXPERIMENT.
- HOW COULD "POINT INTERACTION" COME ABOUT

$\rightarrow$ GENERALLY TRUE IF $q^2 \ll$ GAUGE BOSON MASS



- LOW ENERGY APPROXIMATION

$$\mathcal{M} \sim \bar{u}' u \, \bar{v}' v \cdot G_F$$

$$\hookrightarrow \frac{g^2}{q^2 - M_W^2} \sim \frac{g^2}{M_W^2}$$

IF $g \approx e$

BUT M_W^2 LARGE

INTERACTION LOOKS WEAK AT LOW q^2

FOUR FERMI INTERACTION

- FERMI GUESSED WEAK INTERACTION SAME STRUCTURE AS ELECTROMAGNETISM

$$\mathcal{M} = G(\bar{p}\,\gamma_\mu n)(\bar{e}\,\gamma^\mu \nu_e)$$

SPINOR

$$pe \to n\nu_e$$

$\gamma_\mu \to$ VECTOR INTERACTION

- MORE GENERALLY COULD BE ANY:

$\bar{p}n\,\bar{e}\nu_e$	SCALAR
$\bar{p}\gamma_\mu n\,\bar{e}\gamma^\mu\nu_e$	VECTOR
$\bar{p}\sigma_{\mu\nu} n\,\bar{e}\sigma^{\mu\nu}\nu_e$	TENSOR
$\bar{p}\gamma_\mu\gamma_5 n\,\bar{e}\gamma^\mu\gamma_5\nu_e$	AXIAL VECTOR
$\bar{p}\gamma_5 n\,\bar{e}\gamma_5\nu_e$	PSEUDO SCALAR

$\to$ SO, GUESS

IF ASSUME PARITY CONSERVED

BETA DECAY $n \to p e^- \bar{\nu}_e$

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \sum_{j=SVATP} \int C_j \bar{p} O_j n \cdot \bar{e} O_j \nu_e \, d^3x$$

$$O_j = \underset{S}{1}, \underset{V}{\gamma_\lambda}, \underset{T}{\sigma_{\lambda\nu}}, \underset{A}{\gamma_\lambda \gamma_5}, \underset{P}{\gamma_5}$$

$C_j \Rightarrow$ COUPLING CONSTANTS

- IF ALLOW PARITY VIOLATION

$$(\bar{p} O_j n)(\bar{e} O_j (C_j - C_j' \gamma_5) \nu_e)$$

EVEN ODD

CAN BE COMPLEX IF T-INVARIANCE NOT ASSUMED

10 COMPLEX CONSTANTS TO DETERMINE

EXPERIMENTAL CONCLUSION!

STUDY OF NUCLEAR β DECAY PROVED

VECTOR (γ^μ) NOT ENOUGH

- NEED V AND A

  ↑ AXIAL VECTOR

$$\gamma^\mu \longrightarrow \gamma^\mu(1-\gamma_5)$$

$$\gamma_\mu \qquad \gamma_\mu\gamma^5$$

V — EM

V — A → V−A — WEAK

γ_5 PROJECTS OUT LEFT HANDED PART OF SPINOR

$$(1-\gamma_5)u = \begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \chi \\ \phi \end{pmatrix} = \begin{pmatrix} \chi \\ 0 \end{pmatrix}$$

PROJECTS LEFT HANDED HELICITY FOR PARTICLE STATES

PARITY VIOLATION

SKETCH OF WEAK INTERACTIONS

- ALL MATTER FERMIONS INTERACT WEAKLY

LEPTONS e^-_R μ^-_R τ^-_R $B = 0$

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}_{\text{LEFT}} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}_L$$

$Q = -1.0\,e$

$Q = 0$

LEPTON FLAVOR $\longrightarrow$

CHARGED LEPTON MASS $\longrightarrow$

QUARKS

$B = 1/3$

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

$Q = \frac{2}{3} \cdot e$

$Q = -\frac{1}{3} \cdot e$

QUARK FLAVOR $\longrightarrow$

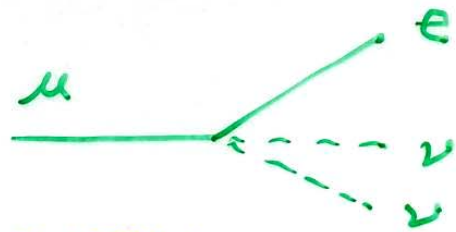
QUARK MASS $\longrightarrow$

- HOW DO WE KNOW THAT THIS GENERATION STRUCTURE EXISTS?

LEPTON FLAVOR CONSERVATION

- EXPERIMENTALLY

$$\mu^- \to e^- \nu \nu$$



- $\nu\nu \to e^-$ ENERGY SPECTRUM
- ARE 2 ν SAME KIND ?

NEVER SEE (SO FAR!) $< 10^{-11}$

$$\mu^- \to e^- \gamma$$

- HYPOTHESIS IS THAT LEPTON GENERATION FLAVOUR SEPARATELY CONSERVED

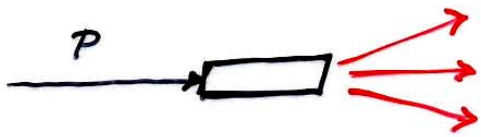
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

EXPERIMENTAL TEST $\nu_e \neq \nu_\mu$

- CHARGED CURRENT ν SCATTERING

$$\nu_\mu N \to \mu^- X$$

HOW IS THIS LABELED?



WHY?

$\pi \to \mu \nu_\mu \sim 100\%$

$\pi \to e \nu_e \sim 10^{-4}$

$K \to \mu \nu_\mu \sim 64\%$

$K \to e \nu_e \sim 10^{-5}$

- ν IN BEAM FROM DECAY $= \nu_\mu$

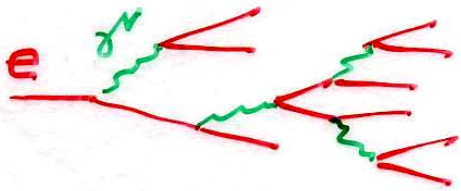
- IF $\nu_\mu \neq \nu_e$ SEE

$$\nu_\mu N \to \mu^- X$$

NEVER

$$\nu_\mu N \to e^- X$$

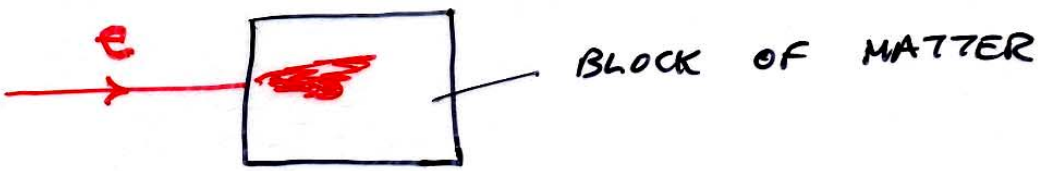
- ELECTRONS IN MATTER FORM ELECTROMAGNETIC SHOWER

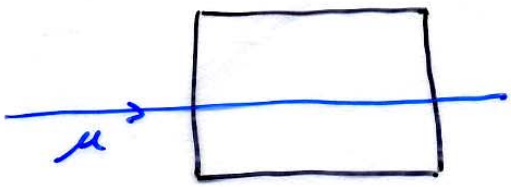


BREMSTRAHLUNG $\sim \dfrac{e^2}{m^2c^4}$

$$P_B(\mu) \approx \frac{P_B(e)}{40{,}000}$$

MUONS LOSE ENERGY BY IONIZATION





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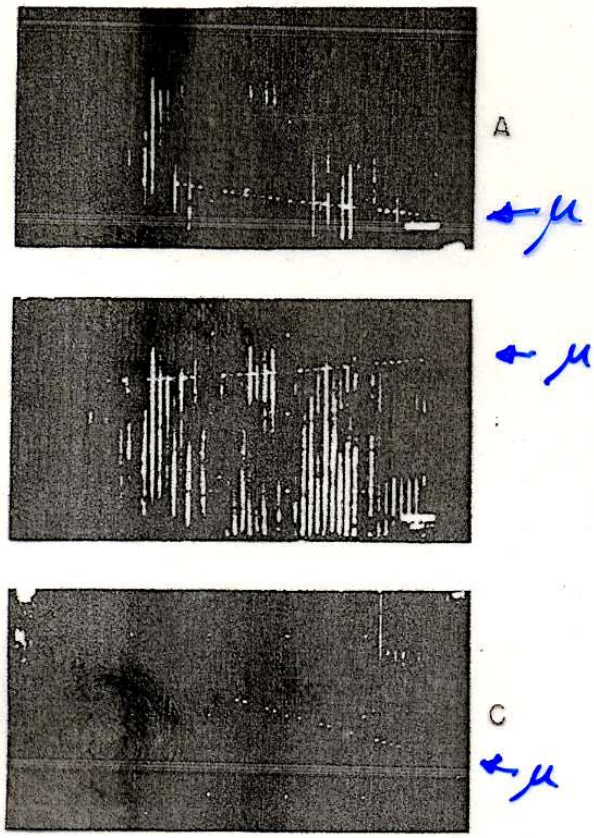


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and ay indicating direction of motion (neutrino beam in- ent from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with ay.

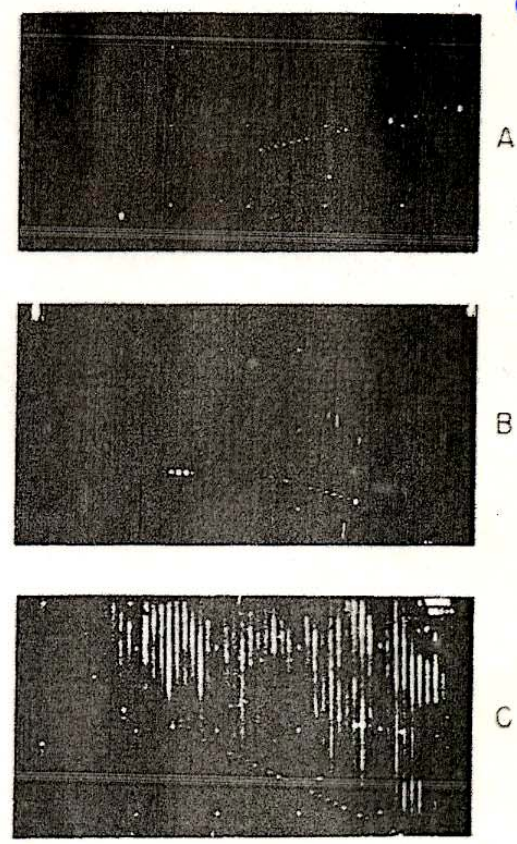
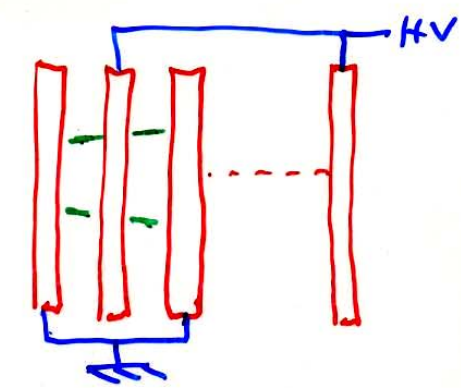


FIG. 6. Vertex events. (A) Single muon of $p_\mu > 50$ MeV and electron-type track; (B) possible example o two muons, both leave chamber; (C) four prong star one long track of $p_\mu > 600$ MeV/c.



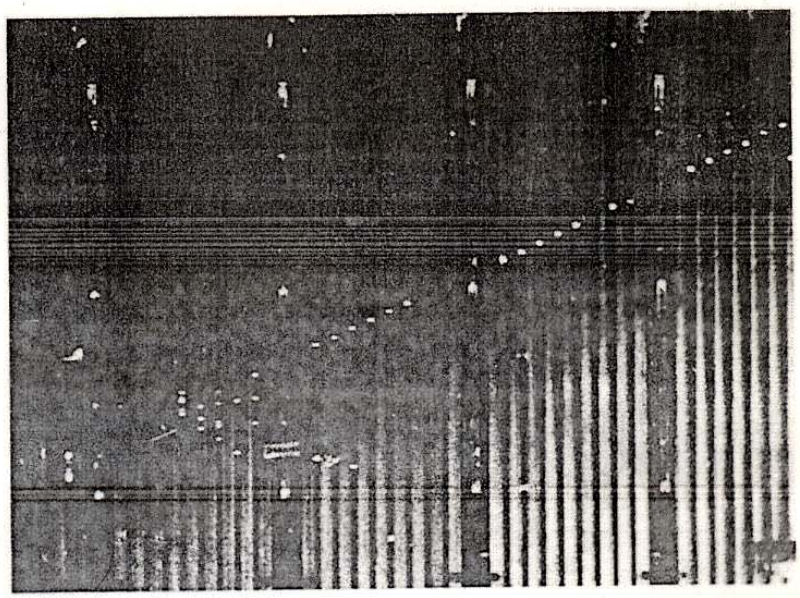
SPARK CHAMBER

- ACTUALLY THERE IS A FLAW IN ALL THIS
- WHAT ABOUT

$\nu_\mu N \rightarrow \nu_\mu X$?

Nobel Prize 1988

A 1962 neutrino makes its mark – the long tell-tale track of a muon shows up clearly in the ten-ton spark chamber of the world's first experiment using high energy laboratory neutrinos.



At the beginning of the 1960s, new proton synchrotrons were getting into their stride at Brookhaven and at CERN. What physics questions could be answered using these high energy machines?

At about the same time, physicists intrigued by the subtleties of the weak nuclear interaction were asking whether the decays of the pions and kaons copiously produced by high energy proton beams could give a secondary neutrino beam for physics experiments. Neutrino experiments were not new – in the 1950s F. Reines and C.L. Cowan had detected free neutrinos produced from the beta decay of fission products in a nuclear reactor – but the idea of making a neutrino beam in a Laboratory was. As neutrinos interact only through the weak nuclear force, perhaps such experiments would reveal vital new information about this force.

Physicists suspected that neutrinos come in two types – those associated with electrons, and those produced along with muons, heavier cousins of the electrons. The clue was that nobody had seen a muon decay into an electron and a gamma ray (photon), a process which otherwise should be commonplace. (Jack Steinberger, for one, had spent a lot of time looking for just this decay.) Theorists also pointed out that even the flimsy understanding they then had of weak interactions would be in trouble unless there were two types of neutrinos, one for electrons, one for muons.

Neutrino physics needed a lot of shielding to screen off other particles, and with low energy neutrinos able to pass virtually unhindered through millions of miles of lead, it also called for a big detector and lots of neutrinos to maximize the chances of catching any. A detector looking for different types of neutrinos also had to be able to distinguish between muons and electrons.

Jack Steinberger and Leon Lederman first met at Columbia University's Nevis Laboratory in New York in 1951 when its 385 MeV synchrocyclotron was just coming on-line – then the highest energy machine in the world. Attending undergraduate courses at Columbia at the time was Mel Schwartz, who went on to become Steinberger's student. When Schwartz returned to Columbia in 1958 after a stint at Brookhaven, the talented trio became intrigued by the possibility of a neutrino experiment at the new Brookhaven Alternating Gradient Synchrotron.

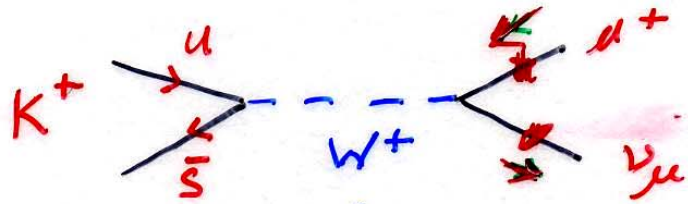
Muons travel long distances without doing much, while electrons quickly dissipate their energy into characteristic showers of particles. Just appearing on the scene at the time was a new kind of detector – the spark chamber. When a high voltage pulse was applied to a series of thin plates, after a charged particle had ionized the gas between the plates, the chamber lit up with a nice track. This seemed to be the way to go, however for neutrinos it meant building a spark chamber bigger than anyone had ever done before.

At Brookhaven the stage was being set for this first physics production using beams of artificial neutrinos. As well as Lederman, Schwartz and Steinberger, the Columbia/Brookhaven team also included Gordon Danby, Jean-Marc Gaillard, Dino Goulianos and Nari Mistry.

Mel Schwartz relates: 'in planning for experiments, I tend to be an optimist, and when we first sat down to do the figures, we said "well, we ought to get one event per ton per day". That was the number we worked with. Actually it turned out to be smaller than that, but fortunately we built a 10-ton detector'.

The massive spark chamber was

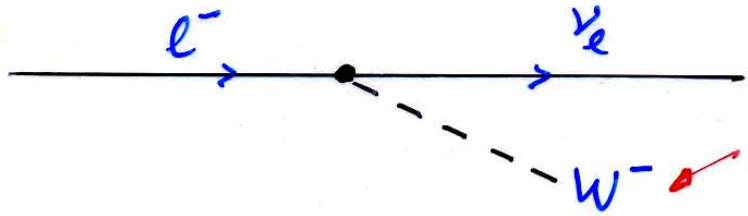
NEED A WEAK PROPAGATOR



$K^+ \to \mu^+ \nu_\mu$

HOPE THIS IS A GAUGE BOSON

LEPTONS

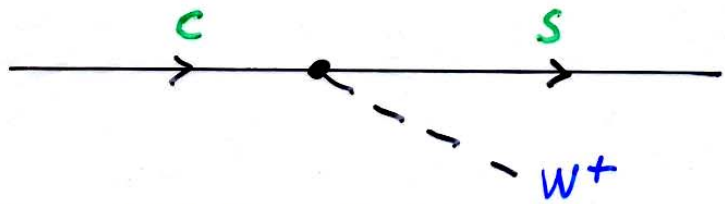


LEFT HANDED PARITY VIOLATING

FLIPS LEPTONS WITHIN DOUBLETS

$\begin{pmatrix} \ell \\ \nu_\ell \end{pmatrix}$ $W^\pm$ FLIPS WITHIN DOUBLET

QUARKS



CHANGES QUARK FLAVOUR

SAME THING IN LEPTON SECTOR WOULD VIOLATE FLAVOUR CONSERVE

$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ W^+

ALSO HAVE THIS