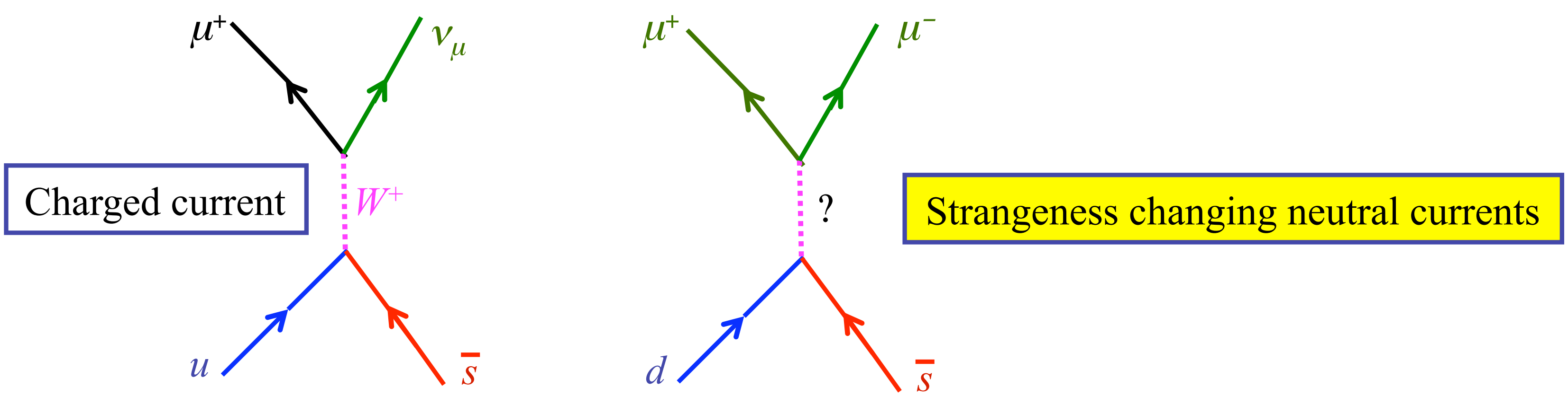
Weak Interactions & Neutral Currents

- Until the the mid-1970's all known weak interaction processes could be described by the exchange of a charged, spin 1 boson, the W boson.
  - Weak interactions mediated by a W-boson are called "charged current" interactions.
- A key prediction of the Glashow-Weinberg-Salam model was the existence of weak interactions mediated by the Z^0, a neutral vector boson.
  - The Z^0 did not change the flavor of the lepton or quark.

M&S CH 9.1

- The GIM mechanism was invented to eliminate (first order) neutral current reactions where the flavor of the quark or lepton changed.
- The measured branching fractions of $K^0 \to \mu^+\mu^-$ and $K^+ \to \mu^+\nu_e$ provided evidence for the absence of flavor (strangeness) changing neutral currents:

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \approx 10^{-8}$$



Weak Interactions & Neutral Currents

- The GIM mechanism eliminated strangeness changing neutral currents by adding a fourth quark (charm):

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

  - Adding the two amplitudes together:

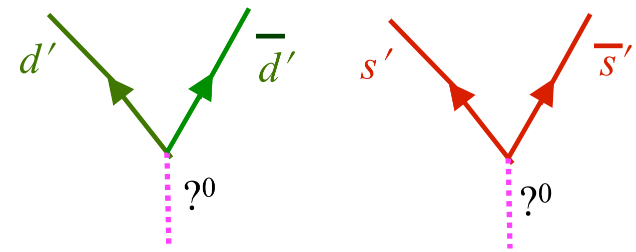
$$\bar{d}'d' = \left[\bar{d}\cos\theta_c + \bar{s}\sin\theta_c\right]\left[d\cos\theta_c + s\sin\theta_c\right]$$

$$= \bar{d}d\cos^2\theta_c + \bar{s}s\sin^2\theta_c + [\bar{d}s + \bar{s}d]\cos\theta_c\sin\theta_c$$

$$\bar{s}'s' = \bar{d}d\sin^2\theta_c + \bar{s}s\cos^2\theta_c - [\bar{d}s + \bar{s}d]\cos\theta_c\sin\theta_c$$

$$\bar{d}'d' + \bar{s}'s' = \bar{d}d + \bar{s}s$$

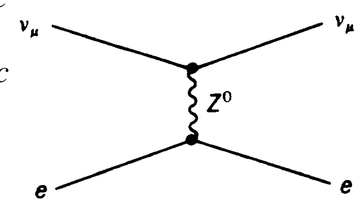
    - The strangeness changing terms are gone but there are still neutral current terms!



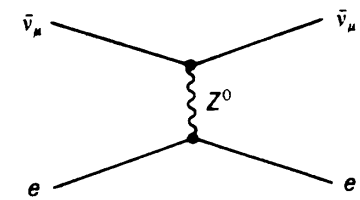
- 1973: found first experimental evidence for neutral currents:

$$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$$

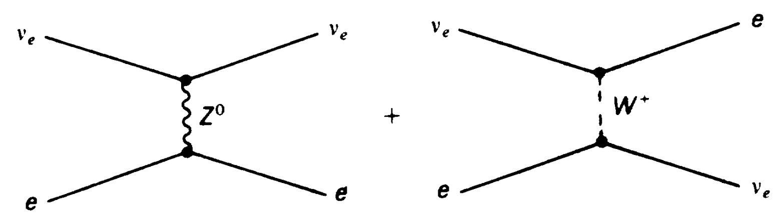
  - This reaction cannot occur by W exchange!



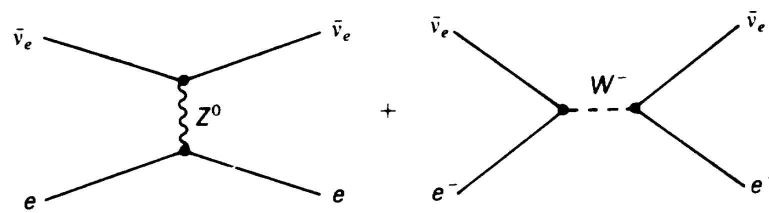
(i) $\nu_\mu e \rightarrow \nu_\mu e$



(ii) $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$



(iii) $\nu_e e \rightarrow \nu_e e$



(iv) $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$

How to Produce a Neutrino Beam?

- Where do the neutrinos come from?
  - Proton-nucleon collisions produce lots of π's and K's which decay into neutrinos.

Neutrino Beam	Anti-Neutrino Beam	Branching Ratio
$\pi^+ \to \mu^+ \nu_\mu$	$\pi^- \to \mu^- \bar{\nu}_\mu$	0.999
$\pi^+ \to e^+ \nu_e$	$\pi^- \to e^- \bar{\nu}_e$	$\approx 10^{-4}$
$K^+ \to \mu^+ \nu_\mu$	$K^- \to \mu^- \bar{\nu}_\mu$	0.63
$K^+ \to e^+ \nu_e$	$K^- \to e^- \bar{\nu}_e$	$\approx 10^{-5}$
$K^+ \to \pi^0 \mu^+ \nu_\mu$	$K^- \to \pi^0 \mu^- \bar{\nu}_\mu$	≈ 0.03
$K^+ \to \pi^0 e^+ \nu_e$	$K^- \to \pi^0 e^- \bar{\nu}_e$	≈ 0.05

  - Also get neutrinos from muon decay with branching ratio of 100%:

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \qquad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

- Rough calculation of ν_μ/ν_e ratio:
  - neglect neutrinos from muon decay.
  - assume we produce 10X as many pions as kaons in a proton-nucleus collision.

$$\frac{\#\nu_\mu}{\#\nu_e} \approx \frac{(\pi \to \nu_\mu)+(K \to \nu_\mu)}{(\pi \to \nu_e)+(K \to \nu_e)} \approx \frac{10BR(\pi^+ \to \mu^+\nu_\mu)+BR(K \to \mu^+\nu_\mu)+BR(K \to \pi^o\mu^+\nu_\mu)}{10BR(\pi^+ \to e^+\nu_e)+BR(K \to e^+\nu_e)+BR(K \to \pi^o e^+\nu_e)}$$

$$\approx \frac{10\times 0.999+0.63+0.03}{10\times 10^{-4}+10^{-5}+0.05} \approx \frac{10.7}{0.05} \approx 210$$

  - Relatively easy to make a beam of high energy ν_μ's, but hard to make a "pure" beam of high energy ν_e.
  - To make a pure beam of ν_e's use nuclear β decay which is below the energy threshold to produce μ's.

Neutrino Induced Neutral Current Interactions

- Many other examples of neutral current interactions were discovered in the 1970's

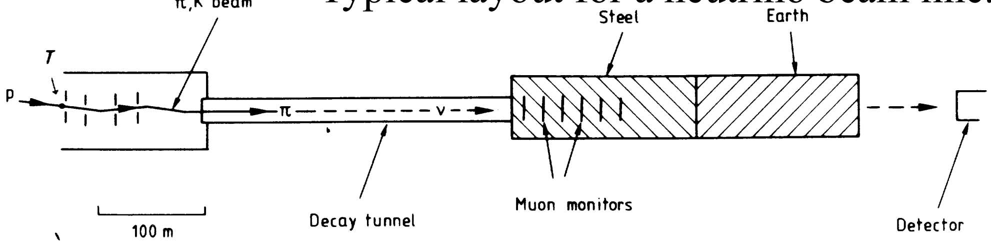
  W exchange (charged current): $\nu_\mu + N \rightarrow \mu^- + X$

  Z exchange (neutral current): $\nu_\mu + N \rightarrow \nu_\mu + X$

  The name derives from the giantess Gargamelle in the works of François Rabelais; she was Gargantua's mother.

  - Neutrino cross section for neutral currents predicted to be 1/3 of charged current cross section.

Typical layout for a neutrino beam line.

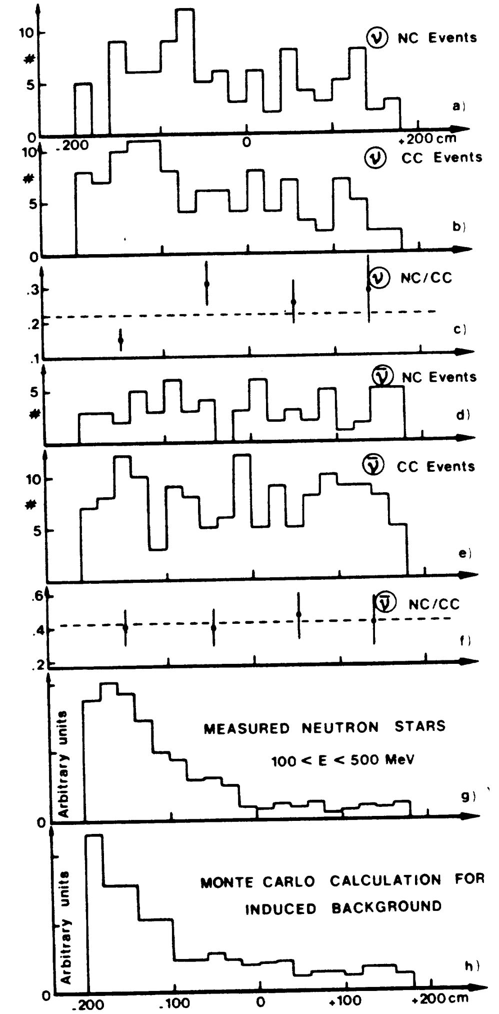


- "Observation of Neutrino-Like Interactions Without Muon or Electrons in the Gargamelle Neutrino Experiment", PL, V45, 1973.
  - CC: charged current event (e or μ in final state)
  - NC: neutral current event (no e or μ in final state)
  - Gargamelle was the name of the bubble chamber (BC).
  - Expect neutrino interactions to be uniformly distributed in BC.
  - Background from neutrons and K^0's expected mostly in front of BC.
  - Data in good agreement with expectation of Standard Model.

$$\left.\frac{NC}{CC}\right|_{\nu} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{27}\sin^4\theta_W = 0.21 \pm 0.03$$

$$\left.\frac{NC}{CC}\right|_{\bar{\nu}} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{9}\sin^4\theta_W = 0.45 \pm 0.09$$

$$\left.\frac{NC}{CC}\right|_{\bar{\nu}} > \left.\frac{NC}{CC}\right|_{\nu}$$



Distributions along beam axis

Neutral Current

- 1983: CERN was able to produce "real" Z's and W's and measure their properties:
  - mass, branching fractions, and decay distributions.
- 1989: accelerators that could produce Z's via $e^+e^- \to Z$ were online:
  - SLC @ SLAC and LEP @ CERN
- 1999: CERN could produce W's via $e^+e^- \to W^+W^-$.
- The model of Glashow, Weinberg and Salam becomes the Standard Model.
  - Coupling of the Z to quarks and leptons is different than the coupling of the W to quarks and leptons.
    - W has a "V-A" coupling to quarks and leptons: $\gamma^\mu(1 - \gamma^5)$
    - Z coupling to quarks and leptons is much more complicated:

$$\gamma^\mu(c_V^f - c_A^f)\gamma^5 = \gamma^\mu(I_3^f - I_3^f\gamma^5 - 2Q^f \sin^2\theta_W)$$

I_3: third component of "weak" isospin

f: fermion type

θ_W: "Weinberg angle"

- a fundamental parameter of the standard model.
- relates the "strength" of the W and Z boson couplings to the EM coupling:

$$g_{EM} = g_W \sin\theta_W$$
$$g_{EM} = g_Z \sin\theta_W \cos\theta_W$$

M&S 9.2.1

$\theta_W \approx 28$ degrees

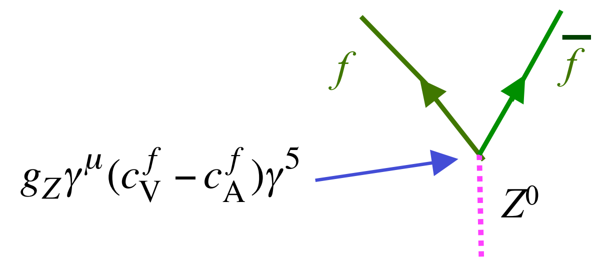
M&S use $g_{EM} = g_Z\cos\theta_W$, eq. 9.8

Neutral Current

- The Standard Model gives us the following for the Z boson coupling to a fermion anti-fermion pair:

$$\gamma^\mu (c_\mathrm{V}^f - c_\mathrm{A}^f)\gamma^5 = \gamma^\mu (I_3^f - I_3^f \gamma^5 - 2Q^f \sin^2\theta_W)$$

f	c_V	c_A	I_3	Q
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
e, μ, τ	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$
d, s, b	$-\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$



- In the Standard Model the masses of the W and Z are related by:

$$M_W = M_Z \cos\theta_W$$

$$M_W = \left(\frac{\sqrt{2} g_W^2}{G_F}\right)^{1/2} = \left(\frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_W}\right)^{1/2} \approx \frac{37.4}{\sin\theta_W}\ \mathrm{GeV/c^2}$$

First order calculation

- Interesting new development (2001) with measurement of $\sin^2\theta_W$:
  - NuTeV is a Fermilab neutrino experiment.
  - NuTeV result: $\sin^2\theta_W = 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$
  - World average: $\sin^2\theta_W = 0.2227 \pm 0.0003$ (mainly from LEP @ CERN)
  - NuTeV result for $\sin^2\theta_W$ disagrees with previous measurements
    - ☞ may point to physics beyond Standard Model or the structure of a proton or neutron is fundamentally modified when it is bound in a nucleus.