Lecture 16

Decays of hadrons

Leptonic : final state contains only leptons

eg. $\pi^- \to \mu^- \bar{\nu}_\mu$,
$K^0 \to \mu^+ \mu^-$

Semi-leptonic : final state has a mixture of leptons and hadrons

eg $K^+ \to \pi^0 \mu^+ \nu_\mu$
$n \to p e^- \bar{\nu}_e$

Hadronic . only hadrons in the final state

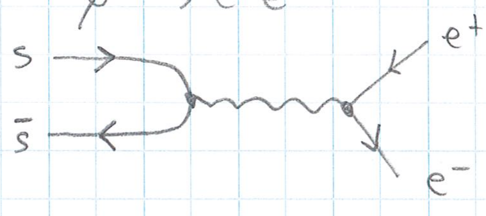
eg , $K^{*0} \to K^+ \pi^-$ (strong decay)

$K^0 \to \pi^+ \pi^-$ (weak decay)
$K^+ \to \pi^+ \pi^0$

Leptonic decays.

consider $\phi = (s\bar{s})$ (almost)

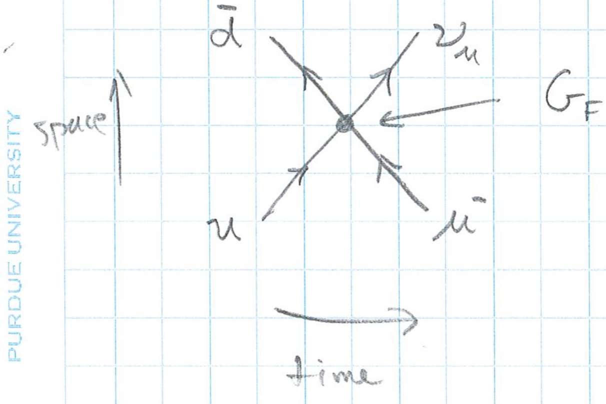
$\phi \to e^+ e^-$



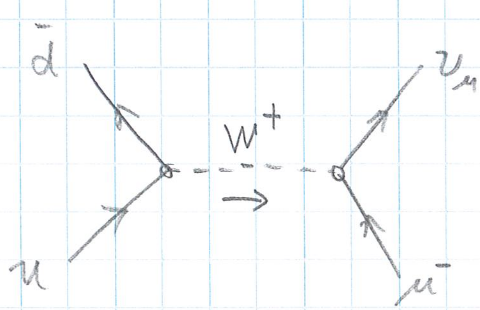
The $s\bar{s}$ pair annihilates . The ϕ has the same quantum numbers as the photon $J = 1$, $P = -1$.

How do we describe weak decays?

Fermi - 4-point interaction

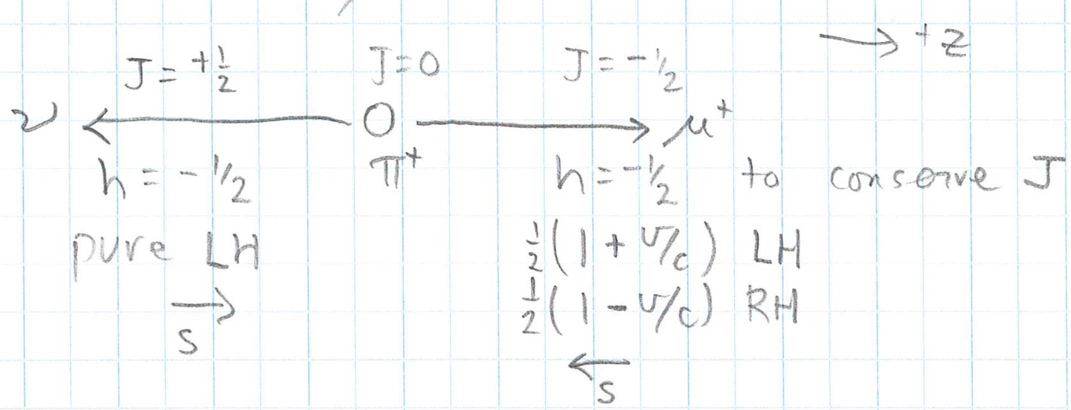


If we want this to look like photon exchange we can introduce a $W^\pm$ gauge boson:



But weak interactions only couple to leptons with "left-handed" helicity, or anti-leptons with "right-handed" helicity.

Neutrinos are only left-handed.



Stated without proof:

Helicity of $J = \pm 1/2$ particle moving in the $+z$ direction is

$$h = \frac{1}{2}\left(1 \pm \frac{v}{c}\right)$$

Helicity of left-handed neutrino moving in the $-z$ direction is $-\frac{1}{2}$.

Spin must be $S_z = +\frac{1}{2}$

Spin of muon must be $S_z = -\frac{1}{2}$

Helicity is $h = \frac{1}{2}(1 + v/c)$ left handed

$\frac{1}{2}(1 - v/c)$ right handed.

$$\beta_e = \frac{v}{c} = \frac{m_\pi^2 - m_e^2}{m_\pi^2 + m_\ell^2}$$

When $\ell = e^-$, $\beta_e = 0.99997$

$\ell = \mu^-$, $\beta_e = 0.272$

So $\frac{(1-\beta_\mu)}{(1-\beta_e)} \sim 20000$

Phase space,

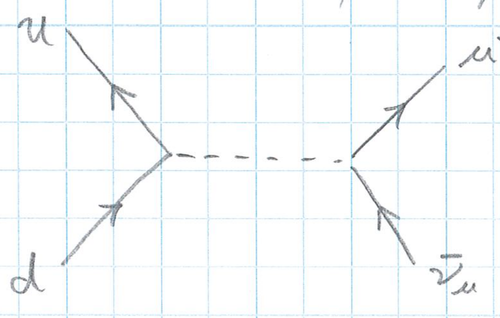
$$\Gamma = \frac{p_f}{8\pi m^2} |\bar{m}|^2$$

Assuming $|\bar{m}|^2$ is the same, then

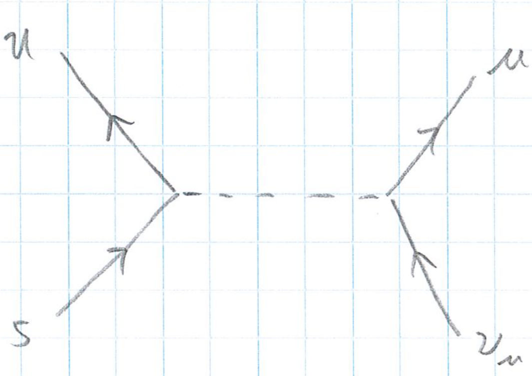
$\frac{\Gamma_e}{\Gamma_\mu}$ is expected to be $\frac{p_e}{p_\mu} = 2.3$

Observed ratio is 1.2×10^{-4}.

π^- decays by $\bar{u}d$ annihilation



K^- must decay by $\bar{u}s$ annihilation



These are the same except for kinematic factors and the Wqq' vertex.

Similarly $n \to p e^- \bar{\nu}_e$ and $\Lambda \to p e^- \bar{\nu}_e$ differ only by the $d \to u$ and $s \to u$ vertex.

These are resolved and universality of the weak interaction is restored if we suppose that the eigenstates of quarks in the weak interactions are

$$d' = d\cos\theta_c + s\sin\theta_c$$

$$s' = -d\sin\theta_c + s\cos\theta_c$$

Strangeness changing neutral currents

We expect $K^+ \to \pi^+ \nu_e \bar{\nu}_e$ should have the same rate as $K^+ \to \pi^0 \nu_e e^+$

But $Br(K^+ \to \pi^+ \nu \bar{\nu}) \sim 1 \times 10^{-10}$
$Br(K^+ \to \pi^0 e^+ \nu) \sim 5 \times 10^{-2}$

$$\bar{d}'d' \sim (\bar{d}\cos\theta_c + \bar{s}\sin\theta_c)(d\cos\theta_c + s\sin\theta_c)$$

$$= \bar{d}d\cos^2\theta_c + (\bar{d}s + \bar{s}d)\cos\theta_c\sin\theta_c + s\bar{s}\sin^2\theta_c$$

$$\bar{s}'s' \sim (-\bar{d}\sin\theta_c + \bar{s}\cos\theta_c)(-\bar{d}\sin\theta_c + s\cos\theta_c)$$

$$= \bar{d}d\sin^2\theta_c - (\bar{d}s + \bar{s}d)\sin\theta_c\cos\theta_c + \bar{s}s\cos^2\theta_c$$

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

But this implies that d, s are parts of a doublet.

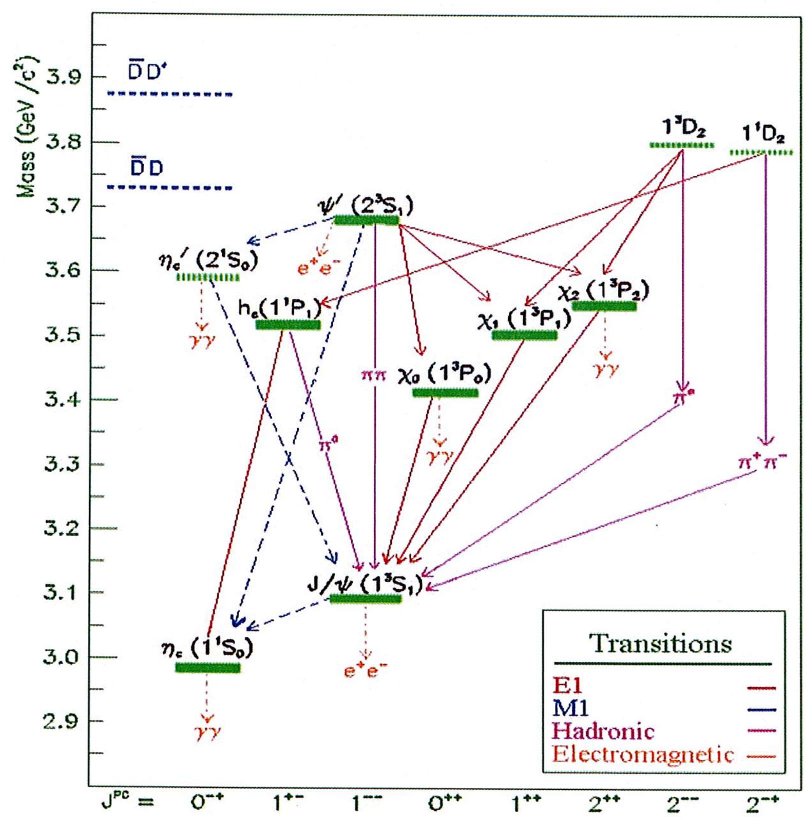
Shouldn't the u-quark also be part of a doublet?

$$\begin{pmatrix} u \\ d' \end{pmatrix} \qquad \begin{pmatrix} ? \\ s' \end{pmatrix}$$

In 1974, $J/\psi \to \mu^+\mu^-$ was discovered at BNL and SLAC, respectively.

Subsequently $\psi' \to \mu^+\mu^-$ was discovered as were a whole spectrum of states:

The charmonium spectrum

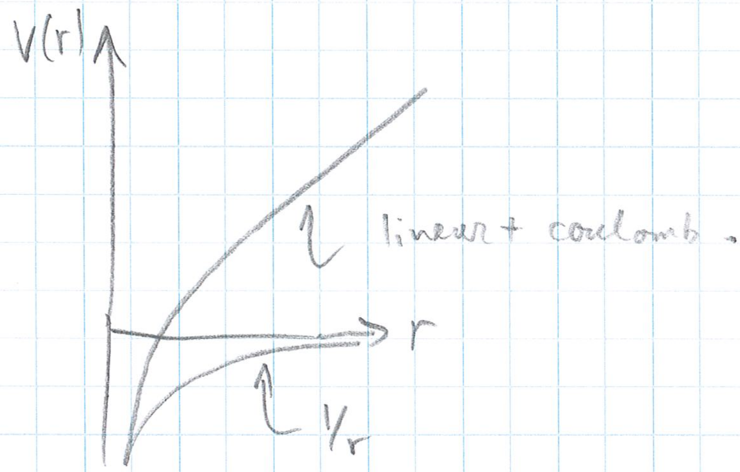


The charm quark is heavy ~ 2 GeV so it is almost nonrelativistic.

$$H\psi = E_n \psi$$

$$H = \frac{p^2}{2m} + V(r)$$

V(r) seemed to be consistent with $\frac{1}{r}$ but was confining as $r \to \infty$.



Alternative models used harmonic oscillator basis states tuning the radius of the ground states.