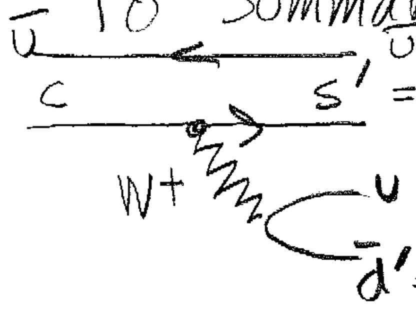
To Summarize ... D^0 Decay



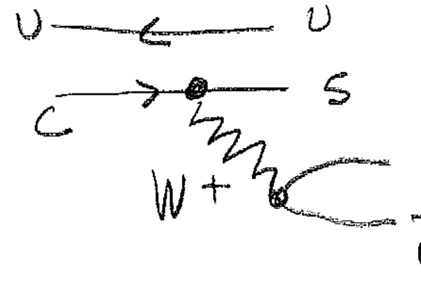
$s' = V_{cs}|s\rangle + V_{cd}|d\rangle + \cancel{V_{cb}|b\rangle}$

not enough energy

$\bar{d}' = V_{ud}|\bar{d}\rangle + V_{us}|\bar{s}\rangle + \cancel{V_{ub}|b\rangle}$

Usually, we're more careless, & just say...

$D^0 \to K^- \pi^+$



$V_{cs}\Big\}\,K^-$

$V_{ud}\Big\}\,\pi^+$

$P \propto |\underbrace{V_{cs} V_{ud}^*}_{\text{both} \simeq 1}|^2$

("Cabibbo Favored")

In "2x2" approximation (useful)

$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

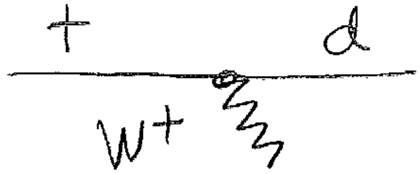
$V_{ud} \simeq 0.97 \simeq V_{cs} \qquad V_{us} \simeq -V_{cd} \simeq 0.24$

"3x3" $\Rightarrow$ small changes; complex # needed

Nobel Prize 2008

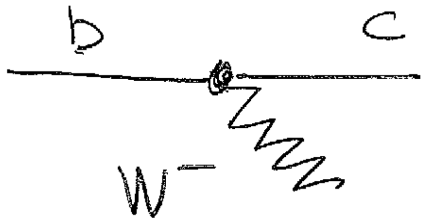
$D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$) $\quad P \propto \sin^2\theta_c \cos^2\theta_c \sim 0.04$

$D^0 \to K^+\pi^-$ $\quad P \propto \sin^4\theta_c \simeq 1.6 \cdot 10^{-3}$



V_{td} (piece of d')

What about ....

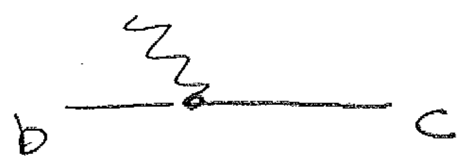


V_{cb}.

$\bar{b}' = V_{cd}\, d + V_{cs}\, s + V_{cb}\, b$

V_{cb}

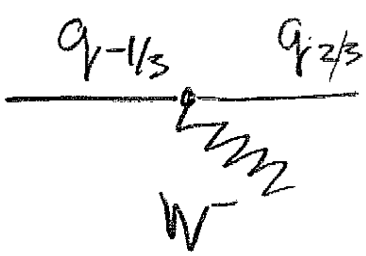
<u>Cross</u>



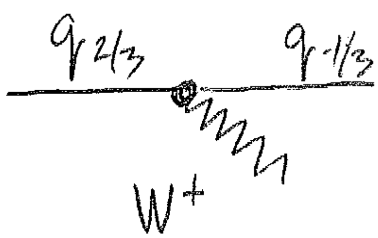
or

V_{cb}

Any



$V_{q_{2/3}\, q_{-1/3}}$



$V_{q_{2/3}\, q_{-1/3}}$ too

<u>ANTIMATTER</u> : <u>Take CC</u>

More about Weak Hadronic Decay

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

Eigenstates of total Hamiltonian

$$d' = V_{ud}\, d + V_{us}\, s + V_{ub}\, b$$
$$s' = V_{cd}\, d + V_{cs}\, s + V_{cb}\, b$$
$$b' = V_{tb}\, d + V_{ts}\, s + V_{tb}\, b$$

"CKM" Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{tb} & V_{ts} & V_{tb} \end{pmatrix}$$

NOT TOO FAR From $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$$= \begin{pmatrix} 0.97 & 0.23 & 0.004\, e^{i80^\circ} \\ 0.23 & 0.97 & 0.04 \\ 0.009\, e^{i22^\circ} & 0.04 & 1.00 \end{pmatrix}$$

Two corners have significant complex values... matter - antimatter asymmetry.

Really only 4 parameters ...

3 real... like angles in 3-d space.

1 complex phase

Cabibbo

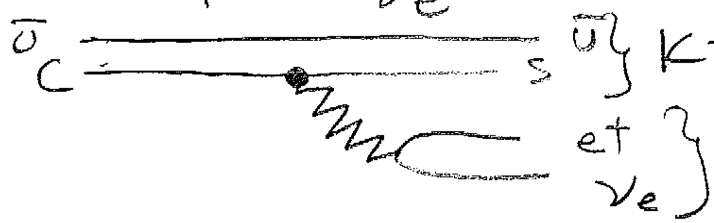
Kobayashi - Maskawa

$D^0 \longrightarrow$ Lots of things!

① "Branching Ratio"

$D^0 \to K^- \pi^+$ $\quad 3.89 \pm 0.05\,\%$
(Weak Hadronic).

$D^0 \to K^- e^+ \nu_e$ $\quad 3.58 \pm 0.06\,\%$



semileptonic

<u>also</u> $D^0 \to K^{*-} e^+ \nu_e$, $D^0 \to K^{(*)} \mu^+ \nu_\mu$.

$D^0 \to \pi^+ \pi^-$ $\quad 1.397 \cdot 10^{-3}$

$D^0 \to K^+ K^-$ $\quad 3.93 \pm 0.08 \cdot 10^{-3}$

suppressed by $\sim \sin^2\theta_c$
(K^+K^- actually enhanced).

$D^0 \to K^+ \pi^-$ $\quad (1.31 \pm 0.08 \cdot 10^{-4})$

suppressed by $\sim \sin^4\theta_c$

② Decaying states in general

$$|\psi(t)|^2 = \Big|\underbrace{\psi_0\, e^{-\frac{imc^2 t}{\hbar}}}_{\text{in rest frame of particle}}\Big|^2 \underbrace{e^{-t/\tau}}_{\text{new! LIFETIME}}$$

so $\Psi(t) = \Psi_0 \, e^{-\frac{imc^2 t}{\hbar} - \frac{1}{2\tau} t}$

Full Width $\quad \frac{\Gamma}{\hbar} \equiv \frac{1}{\tau}$ or $\Gamma = \frac{\hbar}{\tau}$

then

$$\Psi(t) = \Psi_0 \, e^{-\frac{it}{\hbar} \underbrace{\left[mc^2 - i\frac{\Gamma}{2} \right]}}$$

decaying states have imaginary rest energies!

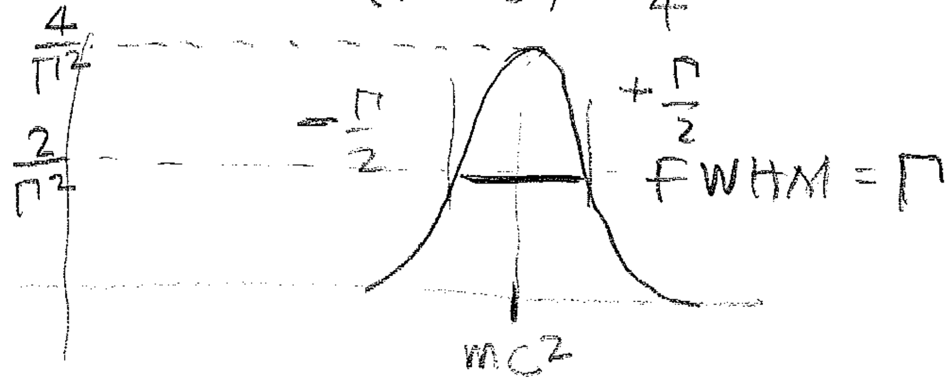
$$\tilde{\Psi}(E) = \int_0^\infty dt \, \Psi(t) \, e^{+\frac{it}{\hbar}E}$$

$$= \Psi_0 \int_0^\infty dt \, e^{\frac{it}{\hbar}\left[\left(E - mc^2 + i\frac{\Gamma}{2}\right)\right]}$$

$$= \frac{\Psi_0}{\frac{i}{\hbar}\left(E - mc^2 + i\frac{\Gamma}{2}\right)} \, e^{\frac{it}{\hbar}\left(E - mc^2 + i\frac{\Gamma}{2}\right)} \Big|_0^\infty$$

$$\tilde{\Psi}(E) = \frac{i\hbar \Psi_0}{E - mc^2 + i\frac{\Gamma}{2}}$$

$$P(E) \propto |\tilde{\Psi}(E)|^2 \propto \frac{1}{(E - mc^2)^2 + \frac{1}{4}\Gamma^2}$$



Practically

$\tau \gtrsim 10^{-18}\,s$] measure lifetime.

$\tau \lesssim 10^{-18}\,s$] measure Energy Width

$$\Gamma = \frac{\hbar}{\tau} = \frac{\hbar c}{c\tau} \cong \frac{200\ \text{MeV}\cdot\text{fm}}{3\cdot 10^{23}\,\frac{\text{fm}}{s}\cdot \tau \cdot 10^{-18}\,s}$$

$$\simeq 70\cdot 10^{-5}\ \frac{1}{\tau(10^{-18}s)}\ \text{MeV}$$

$$\boxed{\Gamma \simeq \frac{700}{\tau(10^{-18}s)}\ \text{eV}}$$

"Strong Interactions" $c\tau \simeq 1$ fm (!)

$\tau \sim \frac{1}{3}\cdot 10^{-23}\,s$

$\sim 3\cdot 10^{-24}\,s$

"1 tick"

$$\Gamma \simeq \frac{700}{3}\cdot 10^{6}\ \text{eV}$$

$$\boxed{\Gamma \sim 200\ \text{MeV}}$$

Z^0 ... Width used to "count neutrinos.