STRANGENESS OSCILLATIONS

- WEAK INTERACTION EIGENSTATES ARE RELEVANT FOR K^0 $\bar{K}^0$ PROPAGATION
- WE DEFINED K^0_1 & K^0_2 → CP EIGENSTATES
- SHORT & LONG LIVED COMPONENTS OF K^0, $\bar{K}^0$ BEAM ARE NOT CP EIGENSTATES → ~~CP~~
- DEFINE

$$K^0_L = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(K^0_2 + \varepsilon K^0_1\right)$$

$$K^0_S = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(K^0_1 - \varepsilon K^0_2\right)$$

LEVEL OF CP VIOLATION

AS $\varepsilon \to 0$

$$K^0_L \to K^0_2$$

$$K^0_S \to K^0_1$$

• PROB AMPLITUDE OF K_S^0 IN REST FRAME

$$A_S(t) = A_S(0)\, e^{-\left(\Gamma_S/2 + i m_S\right)\cdot t}$$

$m_S \rightarrow$ REST MASS OF K_S^0

$\Gamma_S \rightarrow \hbar/\tau_S \rightarrow$ WIDTH OF K_S^0

SIMILARLY $$A_L(t) = A_L(0)\, e^{-\left(\Gamma_L/2 + i m_L\right)t}$$

• START WITH PURE K^0 BEAM FROM STRONG INTERACTION

• FORGET $\cancel{CP}$ $\rightarrow \varepsilon \rightarrow 0$

$$\left.\begin{aligned} K_S^0 &= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \\ K_L^0 &= \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \end{aligned}\right\}$$

$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K_S^0\rangle + |K_L^0\rangle\right)$$

PURE $|K^0\rangle$

$$\therefore A_S(0) = A_L(0) = \frac{1}{\sqrt{2}}$$

- K^0_L & K^0_S EVOLVE DIFFERENTLY IN TIME
- AFTER TIME t

$$I(K^0) = \frac{1}{2}\left[A_S(t) + A_L(t)\right]\left[A_S^*(t) + A_L^*(t)\right]$$

$$= \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m \cdot t\right]$$

$\Delta m = m_L - m_S$

OSCILLATION DEPENDING ON THE MASS DIFFERENCE

SIMILARLY

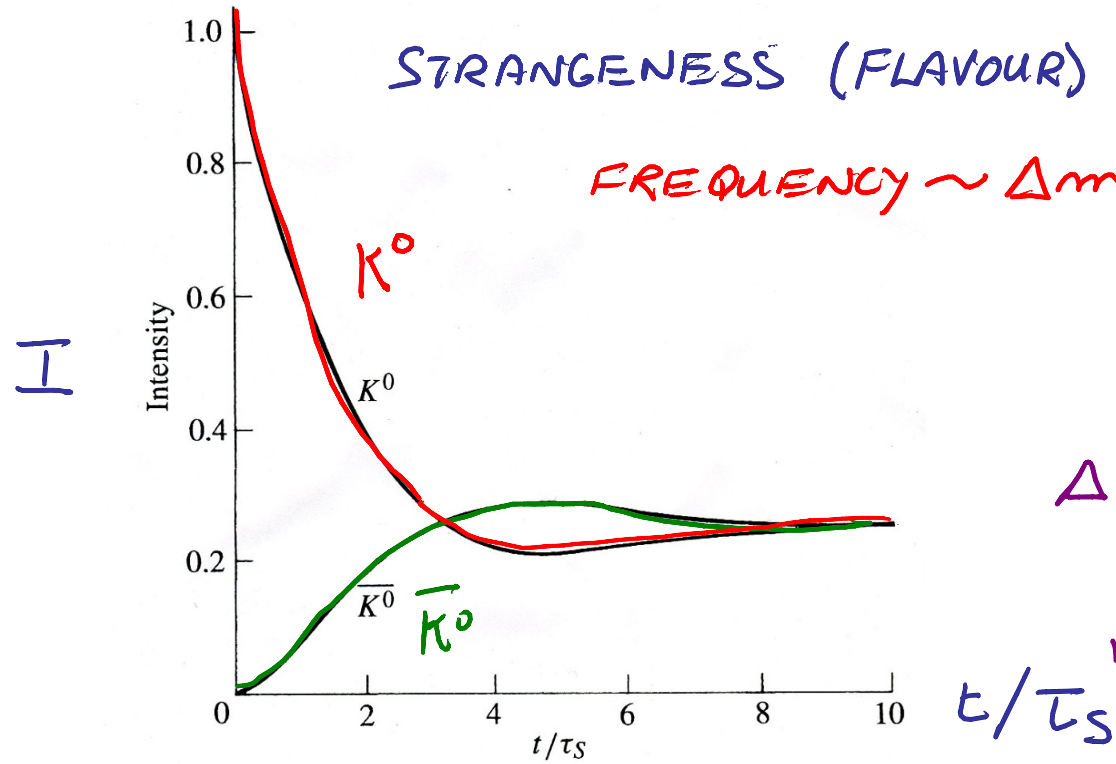
$$I_0(\bar{K}_0) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m \cdot t\right]$$

FLAVOUR OSCILLATIONS

$\Delta m \rightarrow K^0 \leftrightarrow \bar{K}^0$ OSCILLATION FREQUENCY

STRANGENESS (FLAVOUR) OSCILLATIONS

FREQUENCY $\sim \Delta m$



$$\Delta m = \frac{0.5}{\tau_S}$$

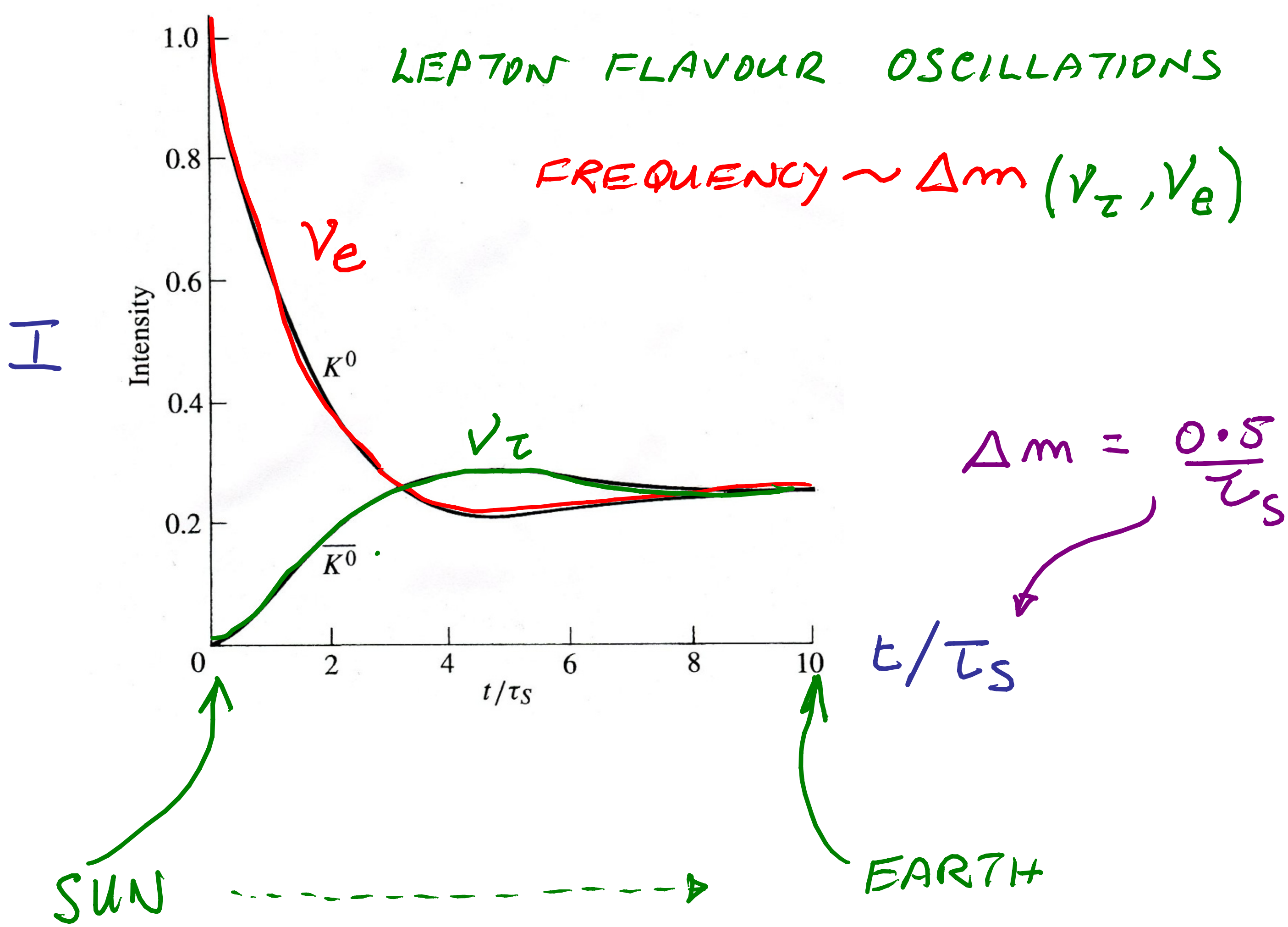
- FOR $K^0\ \overline{K^0}$ SYSTEM $\Delta m = (3.491 \pm 0.009) \times 10^{-12}$ MeV

$$\frac{\Delta m}{m_{K^0}} = 7 \times 10^{-15}$$ ← SENSITIVE TO SMALL Δm

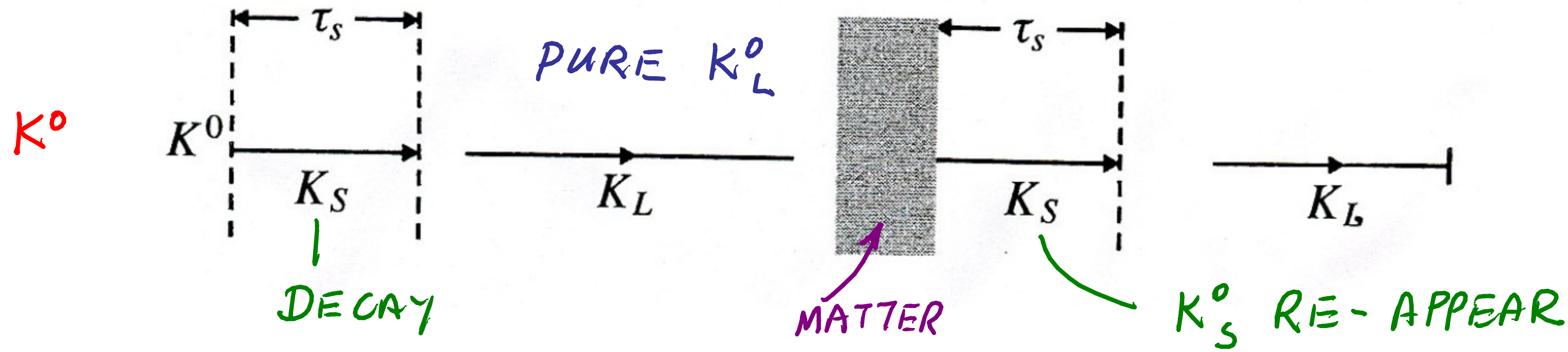
DO LEPTON FLAVOUR OSCILLATIONS EXIST?

→ YOU BET!

TWO ν "MODEL" OF SOLAR ν PROBLEM



FLAVOUR REGENERATION



- PURE $|K^0\rangle$ COASTING IN VACUUM

DECAYS $\longrightarrow$ PURE $|K_L^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$

INTERACT DIFFERENTLY IN MATTER

- AFTER MATTER

$$\left.\begin{array}{l} |\bar{K}^0\rangle \rightarrow \bar{f}\,|\bar{K}^0\rangle \\ |K^0\rangle \rightarrow f\,|K^0\rangle \end{array}\right\} \quad \bar{f} < f < 1$$

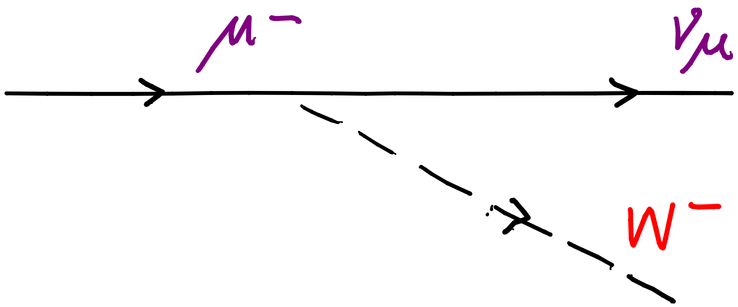
$$\frac{1}{\sqrt{2}}\left(f|K^0\rangle - \bar{f}|\bar{K}^0\rangle\right) = \frac{1}{2}(f+\bar{f})|K_L^0\rangle + \frac{1}{2}(f-\bar{f})|K_S^0\rangle$$

REGENERATED

FLAVOUR MIXING BY WEAK FORCE

WEAK FORCE DOES NOT CONSERVE QUARK FLAVOUR

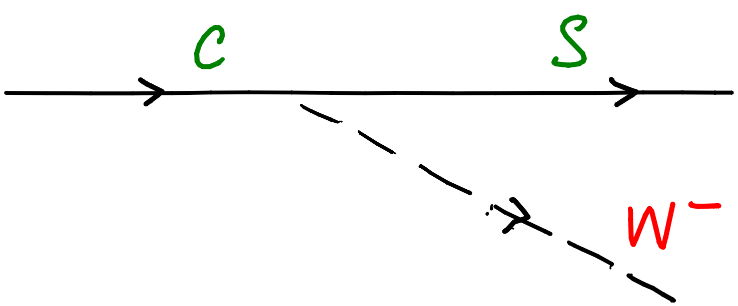
JUST FLIPS LEPTONS WITHIN DOUBLETS



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

$W^\pm$ FLIPS WITHIN DOUBLET

CHANGES FLAVOUR OF QUARKS



$$\begin{pmatrix}u \\ d\end{pmatrix} \qquad \begin{pmatrix}c \\ s\end{pmatrix} \quad W^\pm$$

THINK ABOUT FIRST 2 GENERATIONS

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

→ STATES OF DEFINITE

- MASS
- COLOUR
- FLAVOUR

→ EIGENSTATES OF MASS

$$M|u\rangle = m_u|u\rangle$$

→ EIGENSTATES OF COLOUR FORCE

$$C|u\rangle = c_u|u\rangle$$

THESE CANNOT BE THE EIGENSTATES THAT WEAK INTERACTION SEES → IT DOES NOT CONSERVE QUARK FLAVOUR

EIGENSTATES OF WEAK INTERACTION ARE A MIXTURE OF DEFINITE FLAVOUR STATES

→ THIS IS WHY WEAK INTERACTION CAN INDUCE TRANSITIONS BETWEEN STATES OF DEFINITE FLAVOUR

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad\qquad \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

COLOUR EIGENSTATE = MASS EIGENSTATE

WEAK EIGENSTATES

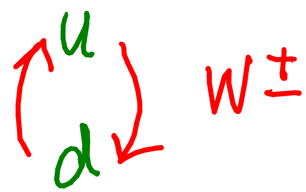
$d \to u \propto \cos^2\theta_c$

$s \to u \propto \sin^2\theta_c$

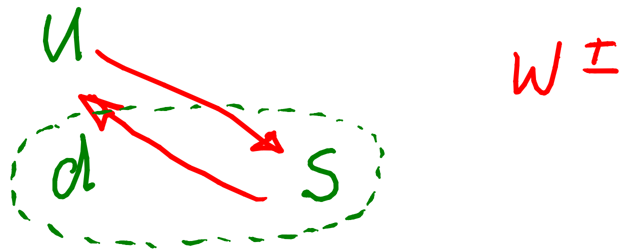
$$\begin{pmatrix} d \\ s \end{pmatrix}_{\text{WEAK}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_{\text{COLOUR}}$$

CABIBBO ANGLE

MAINLY WEAK INTERACTION INDUCES



d & S BEING MIXED — CAN INDUCE



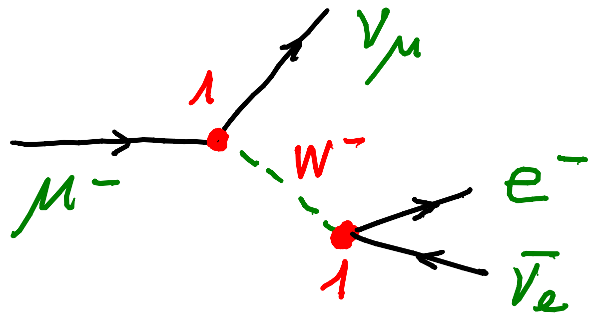
MODIFIES UNIVERSAL FERMION WEAK COUPLING

→ MEASUREMEMENTS CONSISTET WITH UNIVERSAL CABBIBO ANGLE

θ_c

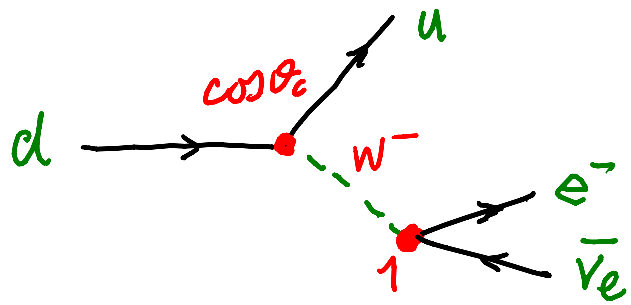
STRENGTH

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



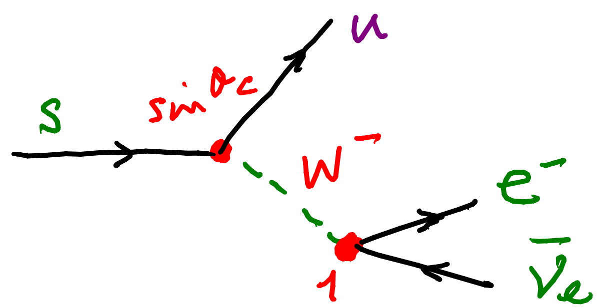
$1 \times G_F^2$

$d \to u e^- \bar{\nu}_e$
($n \to p e^- \nu$)



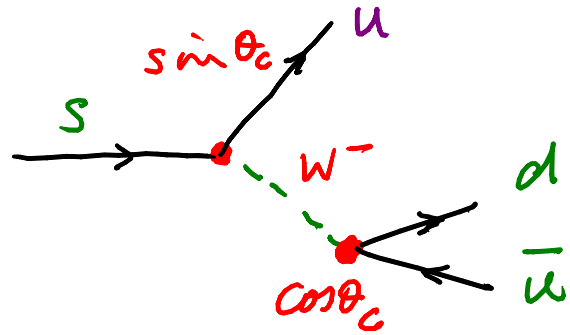
~ 0.95
($\cos^2\theta_c$)

$s \to u e^- \bar{\nu}_e$
($\Lambda \to p e^- \nu$
$Br \sim 10^{-3}$)



~ 0.05
($\sin^2\theta_c$)

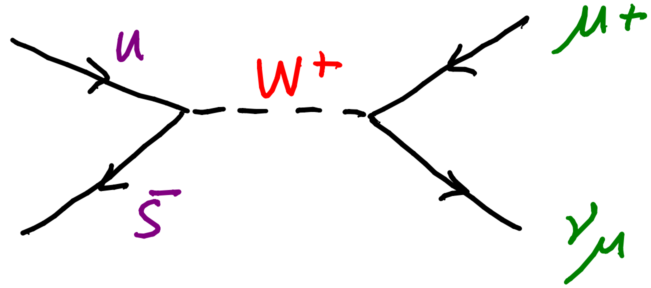
$s \to u d \bar{u}$
($\Lambda \to p \pi^-$)



~ 0.09
($\sin\theta_c \cos\theta_c$)

Z^0 DOES NOT INDUCE DECAYS — WHY?

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



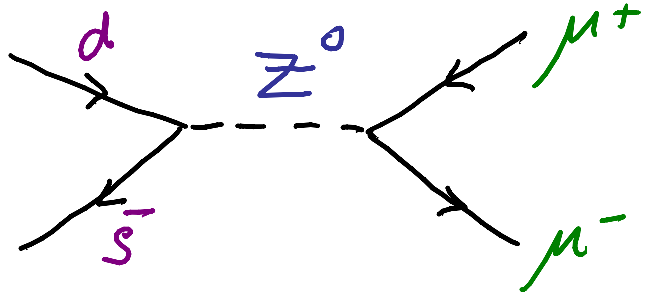
PARITY VIOLATION

$$AMP \sim \frac{G}{\sqrt{2}} \cdot \sin\theta_c \cdot f_K \; m_\mu \, \bar{\nu} \, \gamma_5 \, \mu$$

$$\text{DECAY} \quad \Gamma \sim \frac{G^2}{8\pi} \sin^2\theta_c \, f_K^2 \, m_K \, m_\mu^2 \left(1 - m_\mu^2/m_K^2\right)$$

AGREES WITH EXPERIMENT $\tau \sim 10^{-8}\,s$, $BR \sim 64\%$

$K_L^0 \to \mu^+ \mu^-$



SHOULD BE ABOUT SAME Γ AS THE W^- DIAGRAM

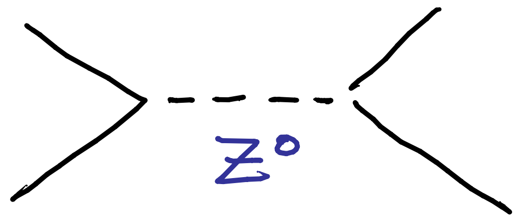
BUT EXPERIMENTALLY $\tau_{K_L} = 5 \times 10^{-8}\,s$

$BR = 9.5 \times 10^{-9}$

NO FLAVOUR CHANGING NEUTRAL CURRENTS

NO FIRST ORDER FLAVOUR CHANGING NEUTRAL CURRENT

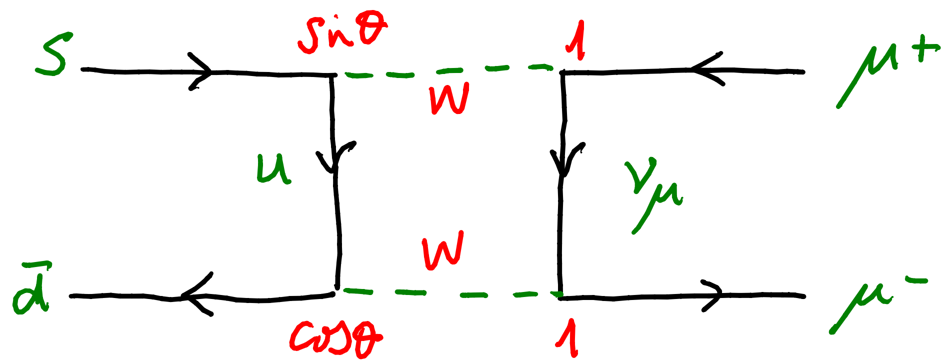
$K_L^0 \to \mu^+ \mu^-$



DOES NOT EXIST

BUT $W^\pm$ CAN INDUCE AT HIGHER ORDER

K_L^0



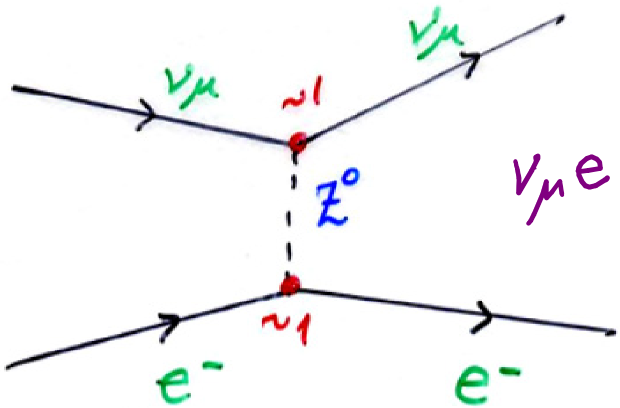
$$\frac{\Gamma(K_L^0 \to \mu\mu)}{\Gamma(K^+ \to \mu\nu)} \gtrsim \left(\frac{3\sqrt{2}\,\alpha}{\pi}\right)^2 \longrightarrow BR\left(K_L^0 \to \mu^+\mu^-\right) \approx 3 \times 10^{-4}$$

Cf EXPERIMENT $BR \sim 10^{-9}$

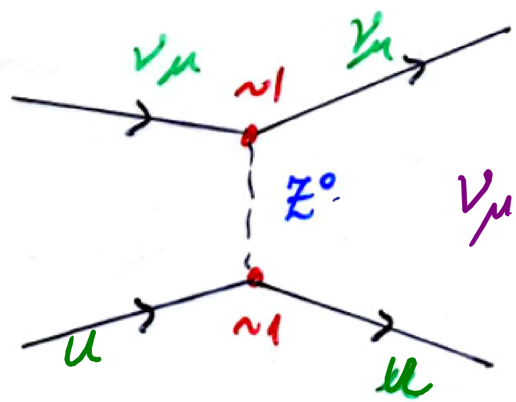
$\Big\{$ SOME SUPPRESSION MECHANISM IS AT WORK HERE

BUT NEUTRAL CURRENTS DO EXIST.

THE FOLLOWING ν INTERACTIONS OBSERVED WITH EXPECTED WEAK COUPLING STRENGTH



$\nu_\mu e \to \nu_\mu e$



$\nu_\mu p \to \nu_\mu p$

NOTICE THAT THESE INTERACTIONS DO NOT CHANGE QUARK FLAVOUR FROM INITIAL TO FINAL STATE

WHY DOES Z^0 NOT INDUCE

$$K^0_L \to \mu^+ \mu^-$$

$S = -1$ $\qquad$ $S = 0$ $\leftarrow$ FLAVOUR CHANGE

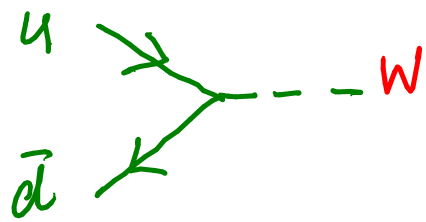
FROM

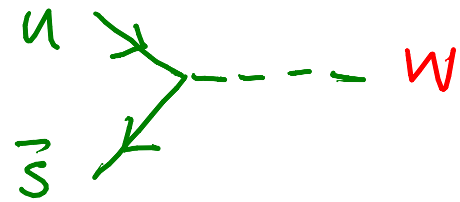
u

$d\cos\theta + s\sin\theta$

WE CAN WRITE THE TRANSITION AMPLITUDES

$\sim u\bar{d}\cos\theta$ $\qquad$ $u\bar{s}\sin\theta$



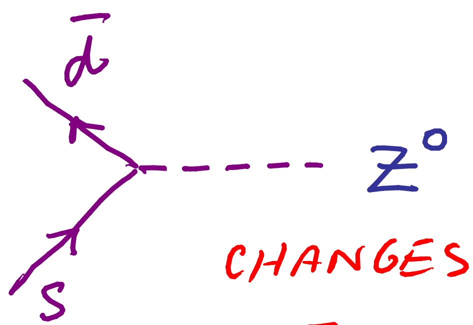


BUT ALSO HAVE

u

$d\cos\theta \quad s\sin\theta$

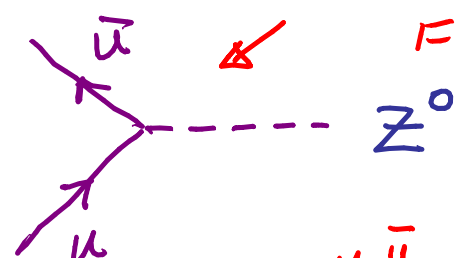
Z^0



CHANGES FLAVOUR

$\sim s\bar{d}\cos\theta\sin\theta$

CONSERVES FLAVOUR



$\sim u\bar{u}$

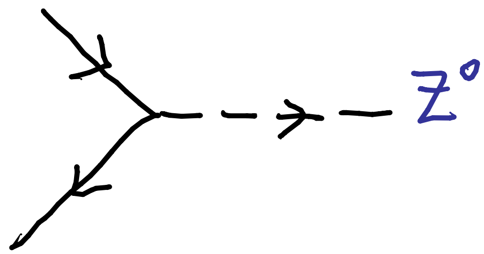
$$\begin{pmatrix} u \\ d\cos\theta \quad s\sin\theta \end{pmatrix}$$

EXPAND OUT ALL POSSIBLE TRANSITIONS FOR Z^0

$u\bar{u} + d\bar{d}\cos^2\theta + s\bar{s}\sin^2\theta$

s, u, d

$\bar{s}, \bar{u}, \bar{d}$



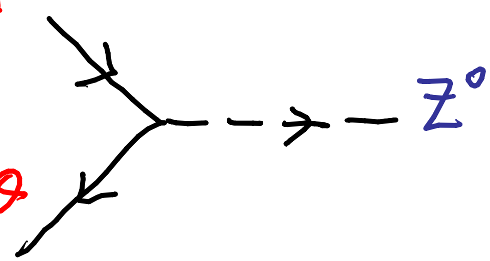
FLAVOUR CONSERVING

OBSERVED IN ν SCATTERING

$s\bar{d}\sin\theta\cos\theta + \bar{d}s\sin\theta\cos\theta$

$d\cos\theta + s\sin\theta$

$\bar{d}\cos\theta + \bar{s}\sin\theta$



FLAVOUR CHANGING

NOT OBSERVED IN DECAY

ABSENCE OF Z^0 DECAYS LED GLASHOW, ILIOPOULOUS & MAIANI TO MAKE THE FOLLOWING PREDICTION BEFORE C-QUARK DISCOVERY

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \rightarrow \text{COLOUR EIGENSTATES}$$

$$\begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix} \qquad \begin{pmatrix} c \\ s\cos\theta - d\sin\theta \end{pmatrix}$$

AS THE WEAK EIGENSTATES

$$\begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix} \quad \begin{pmatrix} \bar{u} \\ \bar{d}\cos\theta + \bar{s}\sin\theta \end{pmatrix}$$

NFC

NFC

FC

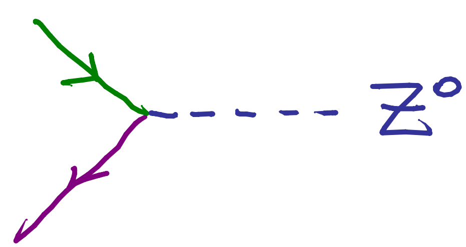
NFC

FC

$$\begin{pmatrix} c \\ s\cos\theta - d\sin\theta \end{pmatrix} \quad \begin{pmatrix} \bar{c} \\ \bar{s}\cos\theta - \bar{d}\sin\theta \end{pmatrix}$$

NFC = NO FLAVOUR CHANGE

FC = FLAVOUR CHANGE



WRITE OUT TRANSITION AMPLITUDES

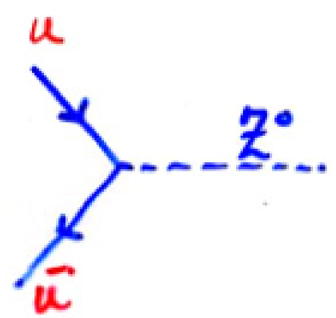
$$u\bar{u} + c\bar{c} + (\bar{d}d + s\bar{s})\cos^2\theta + (s\bar{s} + d\bar{d})\sin^2\theta$$

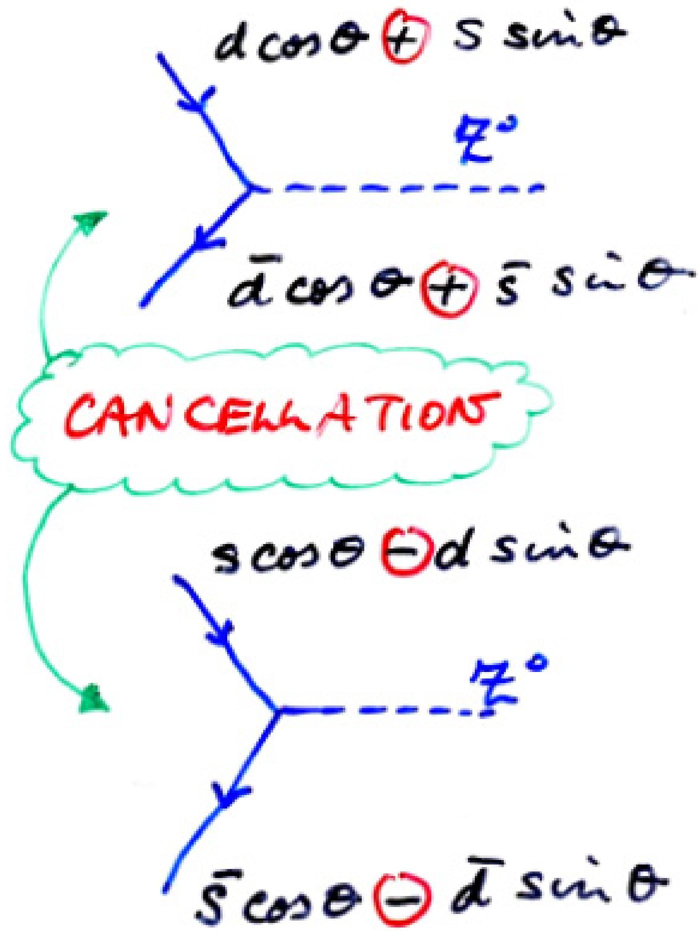
CONSERVES FLAVOUR

$$+$$

$$(s\bar{d} + \bar{s}d - \bar{s}d - s\bar{d})\cos\theta\sin\theta$$

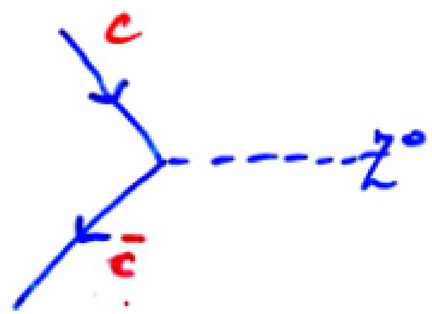
FLAVOUR CHANGING PART VANISHES





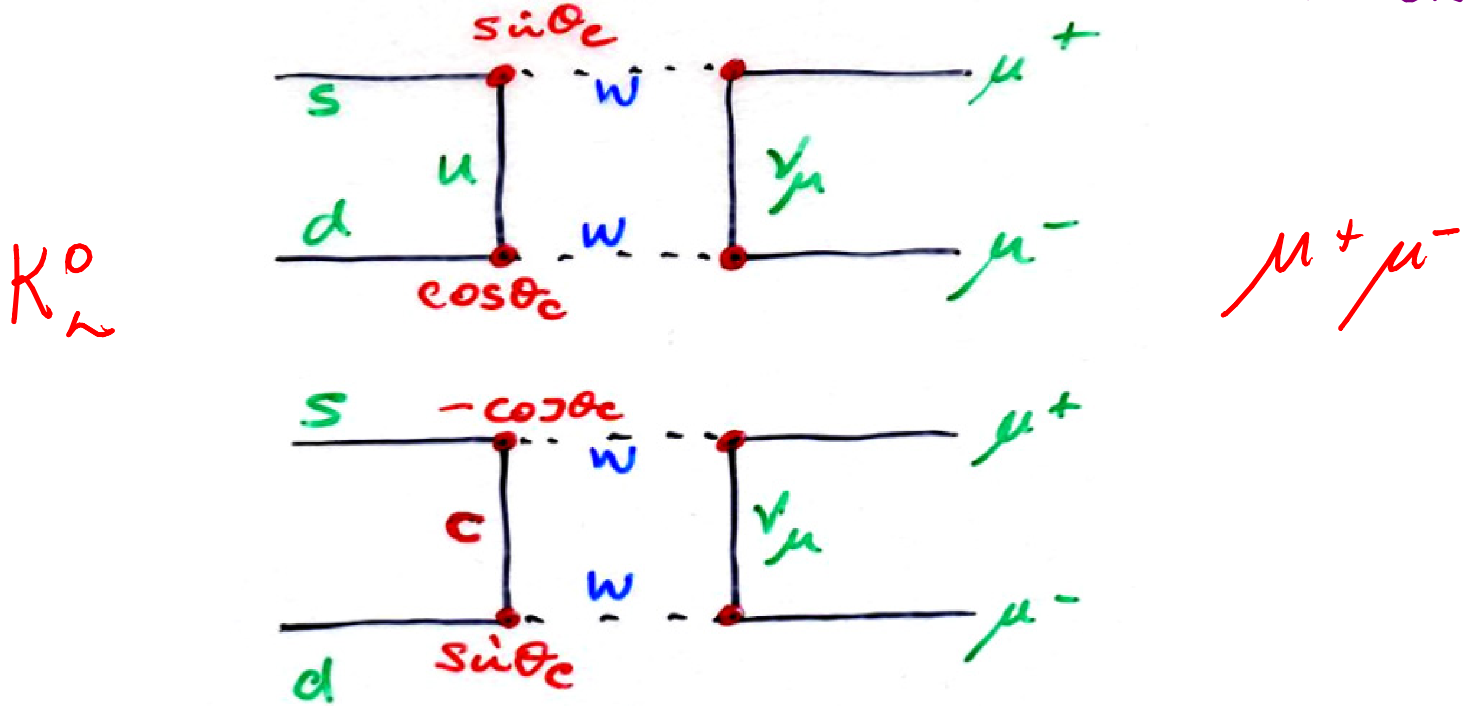
THESE CANNOT MEDIATE DECAYS

$m_u = m_{\bar{u}}$ $m_c = m_{\bar{c}}$



GIM MECHANISM PREDICTED m_{CHARM}

FOR $K_L^0 \to \mu^+\mu^-$ NOW HAVE TWO 2ND ORDER DIAGRAMS



$$BR(K_L \to \mu\mu) \sim 7 \times 10^{-5}\, \frac{m_c^2 - m_u^2}{M_W^2} \ln \frac{M_W^2}{m_u^2}$$

PREDICTED $\to$ $m_c \approx 1.5\ \frac{GeV}{c^2}$ ✓

GENERALLY TRUE THAT THESE BOX DIAGRAMS ARE DOMINATED BY HEAVIEST QUARK THAT CAN CONTRIBUTE TO THE INTERAL LOOP

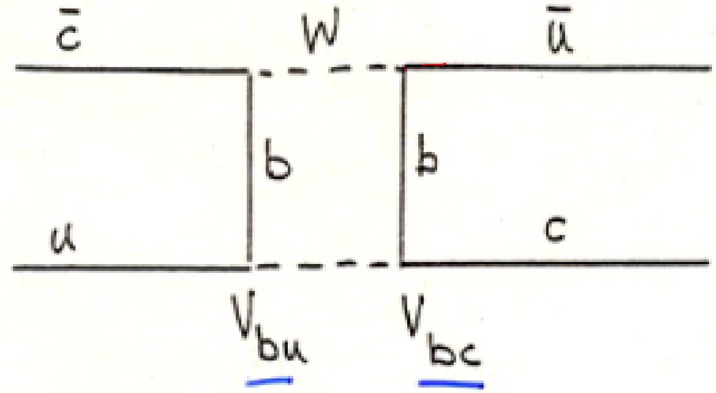
$m_c \rightarrow$ K DECAYS

$m_t \rightarrow B^0\ \bar{B}^0$ MIXING

$m_H \rightarrow$ RADIATIVE CORRECTIONS

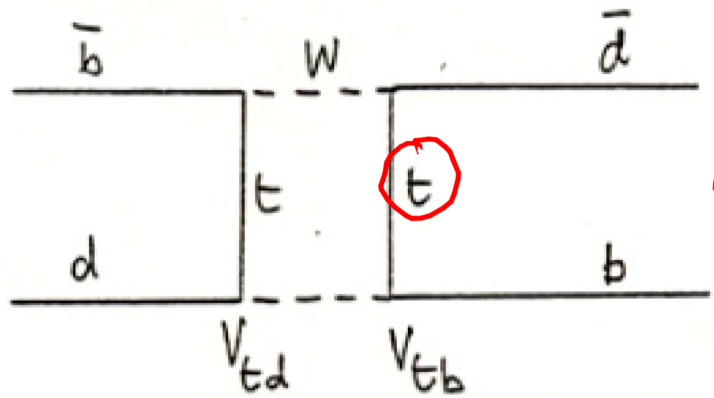
RARE DECAYS CAN ACCESS HIGHER MASS SCALES THAN DIRECT PRODUCTION AT ACCELERATORS

$D^0 \bar{D}^0$



$B_d^0 \bar{B}_d^0$

$e^+e^- \to b\bar{b}$
@ 10 GeV



$m_t > 150 \ \frac{GeV}{c^2}$

$B_s^0 \bar{B}_s^0$