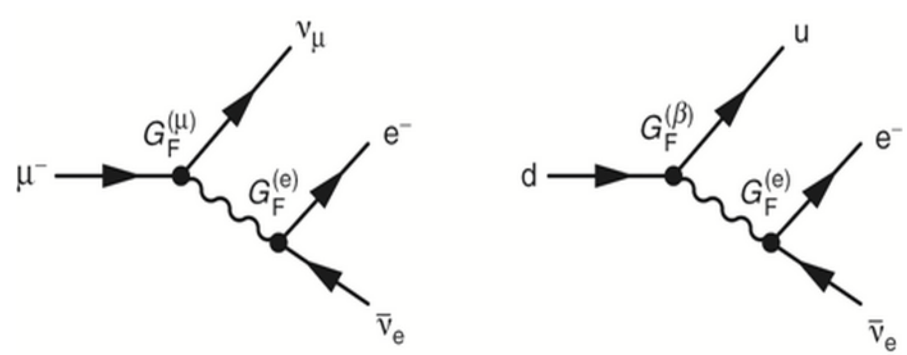
THE WEAK INTERACTION OF QUARKS

ALL LEPTONS HAVE THE SAME COUPLING STRENGTH TO THE WEAK INTERACTION

$$G_F^e = G_F^\mu = G_F^\tau$$

THE SITUATION FOR THE WEAK INTERACTION OF QUARKS IS MORE COMPLICATED, AND MORE INTERESTING



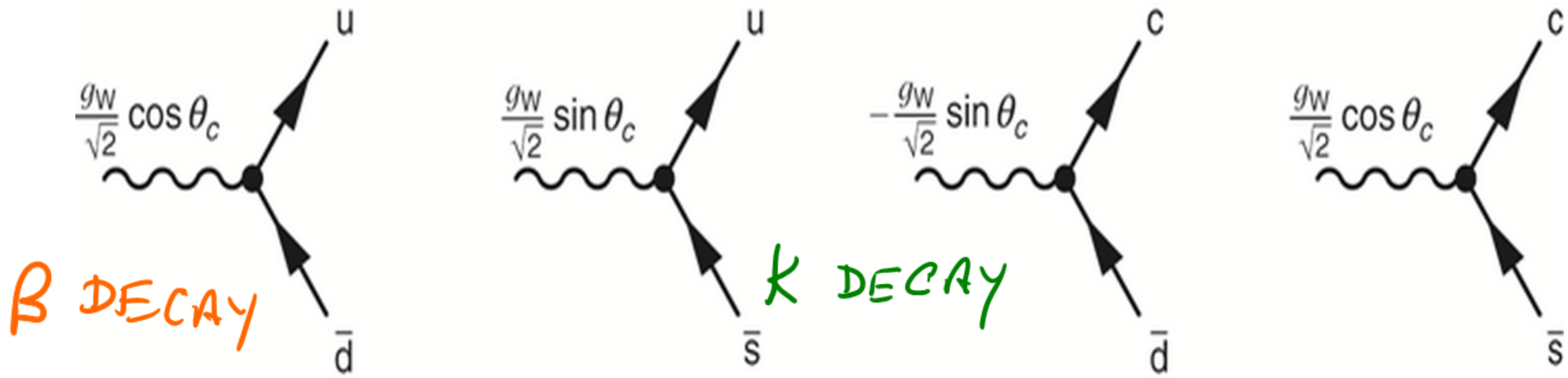
LEPTONIC DECAY

$$|\mathcal{M}^2| \propto \underbrace{G_F^\mu G_F^e}_{\text{EQUAL}}$$

QUARK DECAY

→ β DECAY OF NUCLEUS

$$|\mathcal{M}^2| \propto \underbrace{G_F^e G_F^{(\beta)}}_{???}$$



THE COUPLING OF THE ud QUARK VERTEX IS FOUND TO BE 5% SMALLER THAN $\mu^- \nu_\mu$

$$G_F^{\mu} = (1.1663787 \pm 0.0000006) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$G_F^{\beta} = (1.1066 \pm 0.0011) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

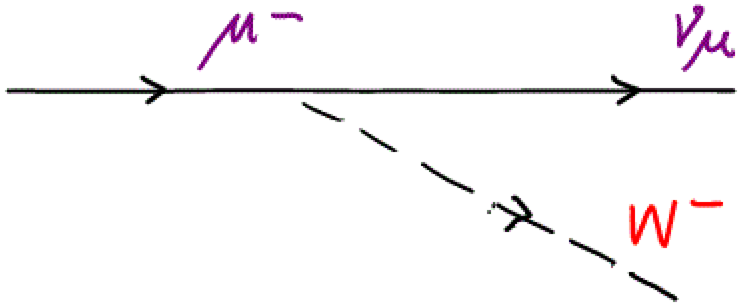
$$\frac{K^-(u\bar{s}) \rightarrow \mu^- \bar{\nu}_\mu}{\pi^-(u\bar{d}) \rightarrow \mu^- \bar{\nu}_\mu} \approx 5\%$$

CLEARLY DIFFERENT FROM LEPTON UNIVERSALITY

FLAVOUR MIXING BY WEAK FORCE

WEAK FORCE DOES NOT CONSERVE QUARK FLAVOUR

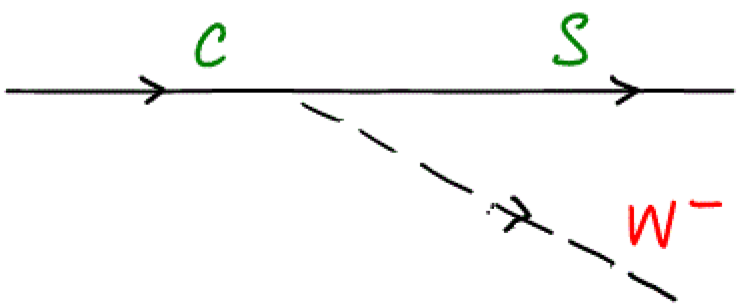
JUST FLIPS LEPTONS WITHIN DOUBLETS



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

$W^{\pm}$ FLIPS WITHIN DOUBLET

CHANGES FLAVOUR OF QUARKS



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

$W^{\pm}$

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

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

COLOUR EIGENSTATE = MASS EIGENSTATE

WEAK EIGENSTATES

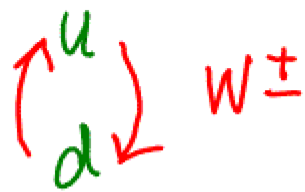
$d \rightarrow u \quad \propto \quad \cos^2\theta_c$

$s \rightarrow u \quad \propto \quad \sin^2\theta_c$

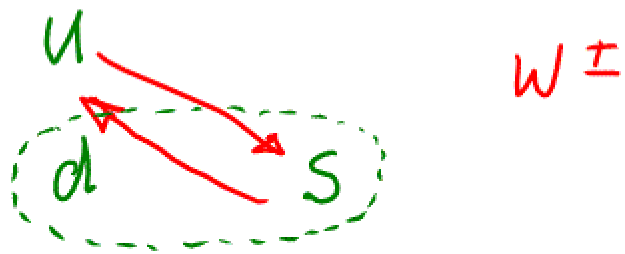
$$\begin{pmatrix} d \\ s \end{pmatrix}_{\text{WEAK}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_{\text{COLOUR}}$$

CABIBBO ANGLE

MAINLY WEAK INTERACTION INDUCES



d & S BEING MIXED — CAN INDUCE



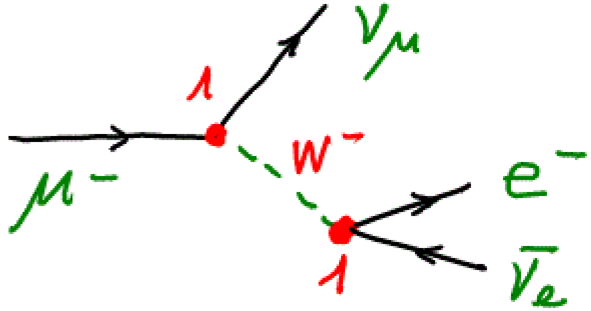
MODIFIES UNIVERSAL FERMION WEAK COUPLING

→ MEASUREMEMENTS CONSISTET WITH UNIVERSAL CABBIBO ANGLE

θ_c

STRENGTH

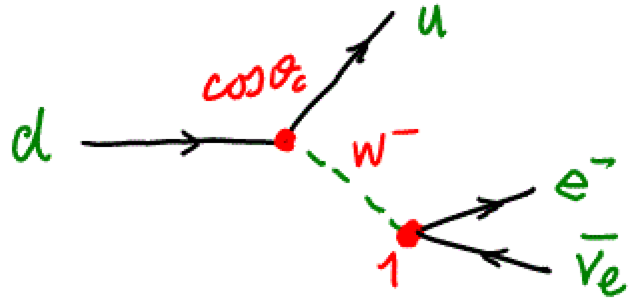
$\mu^- \to \nu_\mu e^- \bar{\nu}_e$



$1 \times G_F^2$

$d \to u e^- \bar{\nu}_e$

$(n \to p e^- \nu)$

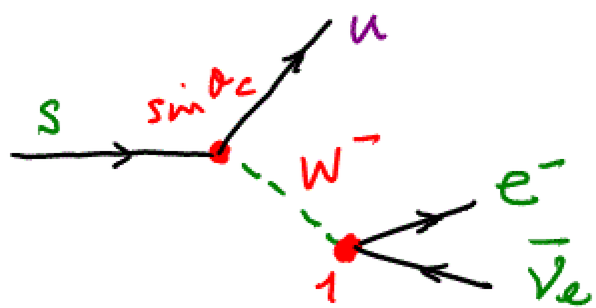


~ 0.95

$(\cos^2\theta_c)$

$s \to u e^- \bar{\nu}_e$

$\left(\begin{matrix}\Lambda \to p e^- \nu \\ Br \sim 10^{-3}\end{matrix}\right)$

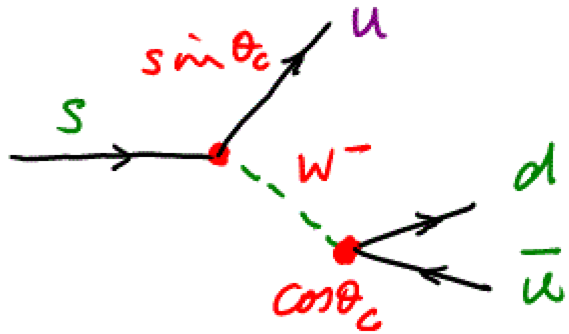


~ 0.05

$(\sin^2\theta_c)$

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

$(\Lambda \to p \pi^-)$

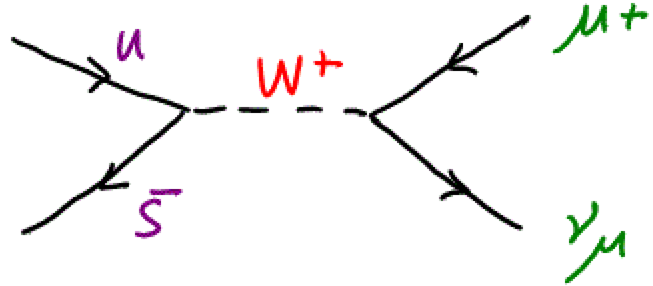


~ 0.09

$(\sin\theta_c \cos\theta_c)$

Z^0 DOES NOT INDUCE DECAYS — WHY?

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



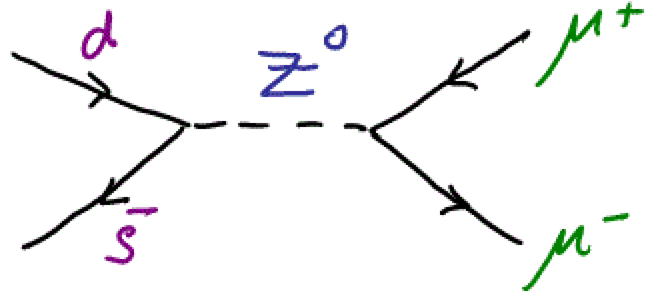
PARITY VIOLATION

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

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

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

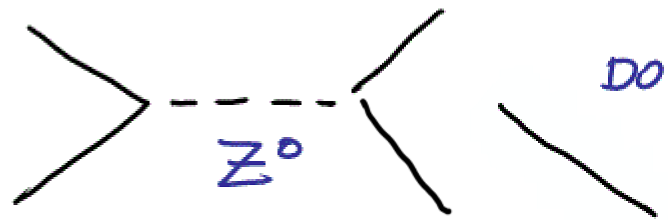
BUT EXPERIMENTALLY $\tau_{K_L} = 5 \times 10^{-8}\,s$

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

NO FLAVOUR CHANGING NEUTRAL CURRENTS

NO FIRST ORDER FLAVOUR CHANGING NEUTRAL CURRENT

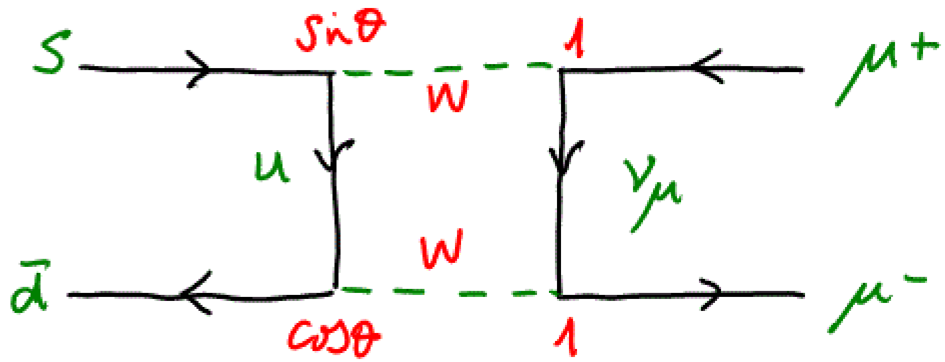
$K^0_L \to \mu^+\mu^-$



DOES NOT EXIST

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

K^0_L

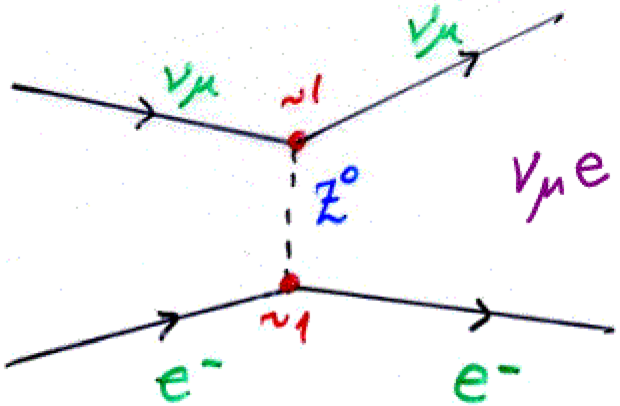


$$\frac{\Gamma(K^0_L \to \mu\mu)}{\Gamma(K^+ \to \mu\nu)} \approx \left(\frac{3\sqrt{2}\,\alpha}{\pi}\right)^2 \longrightarrow BR\left(K^0_L \to \mu^+\mu^-\right) \approx 3 \times 10^{-4}$$

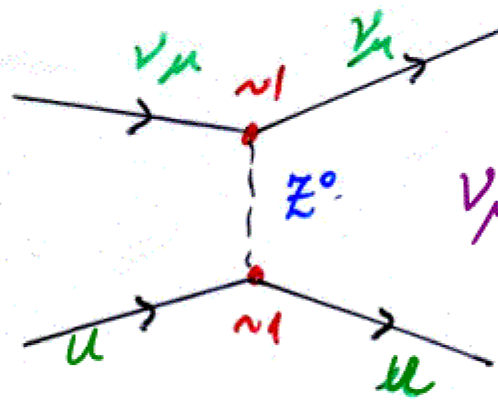
Cf EXPERIMENT $BR \sim 10^{-9}$ $\Big\{$ SOME SUPPRESSION MECHANISM IS AT WORK HERE

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

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

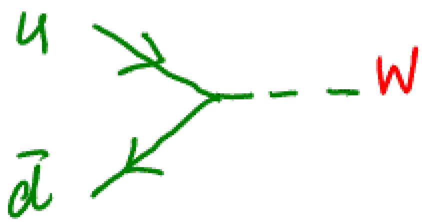
$S = -1$ $\qquad$ $S = 0$ ← FLAVOUR CHANGE

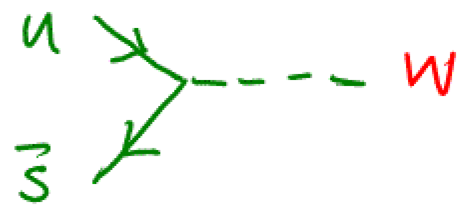
FROM

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

WE CAN WRITE THE TRANSITION AMPLITUDES

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

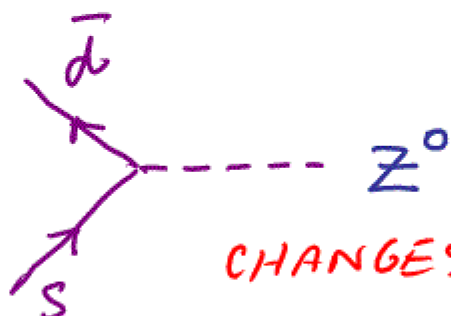




BUT ALSO HAVE

$$u$$

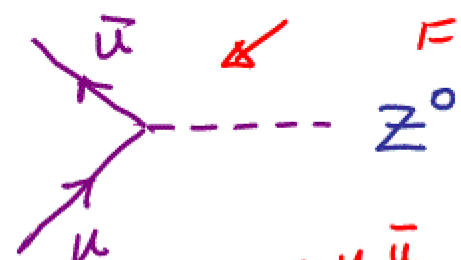
$$d\cos\theta \xleftrightarrow[Z^0]{} s\sin\theta$$



CHANGES FLAVOUR

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

CONSERVES FLAVOUR



$\sim u\bar{u}$

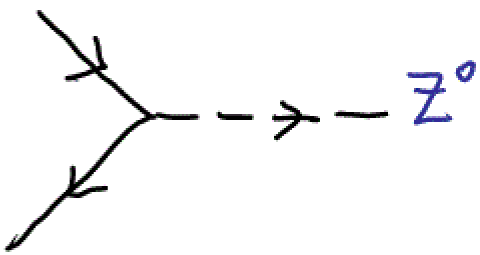
$$\begin{pmatrix} u \\ d\cos\theta \quad s\sin\theta \end{pmatrix}$$

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

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

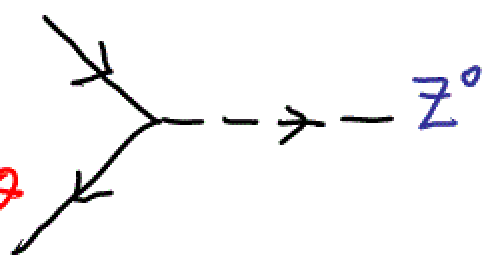


FLAVOUR CONSERVING
OBSERVED IN ν SCATTERING

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

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

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



FLAVOUR CHANGING
NOT OBSERVED IN DECAY

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

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

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

AS THE WEAK EIGENSTATES

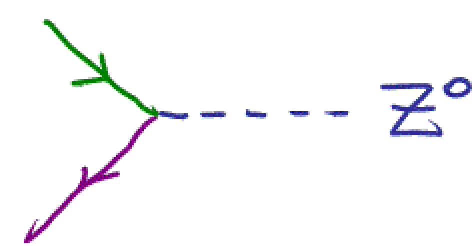
$$\begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix} \qquad \begin{pmatrix} \bar{u} \\ \bar{d}\cos\theta + \bar{s}\sin\theta \end{pmatrix}$$

$$u \xleftrightarrow{\text{NFC}} \bar{u} \qquad d \xleftrightarrow{\text{NFC}} \bar{d} \qquad s \xleftrightarrow{\text{FC}} \bar{d} \qquad s \xleftrightarrow{\text{NFC}} \bar{s} \qquad d \xleftrightarrow{\text{FC}} \bar{s}$$

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

NFC = NO FLAVOUR CHANGE

FC = FLAVOUR CHANGE



WRITE OUT TRANSITION AMPLITUDES

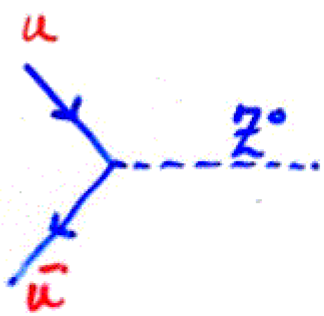
$$u\bar{u} + c\bar{c} + (\bar{d}d + s\bar{s})\cos^2\theta + (s\bar{s} + d\bar{d})\sin^2\theta$$

CONSERVES FLAVOUR

$$+$$

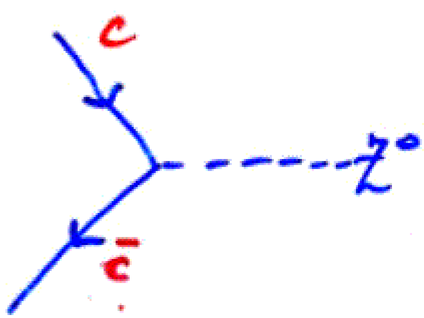
$$(s\bar{d} + \bar{s}d - \bar{s}d - s\bar{d})\cos\theta\sin\theta$$

FLAVOUR CHANGING PART VANISHES

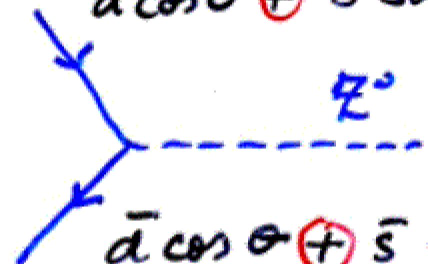


THESE CANNOT MEDIATE DECAYS

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



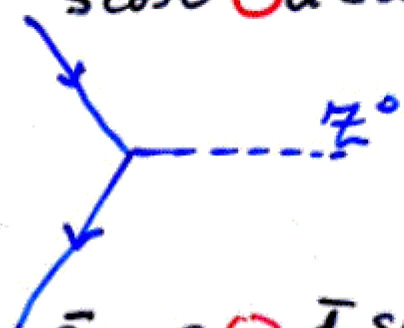
$d\cos\theta + s\sin\theta$



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

CANCELLATION

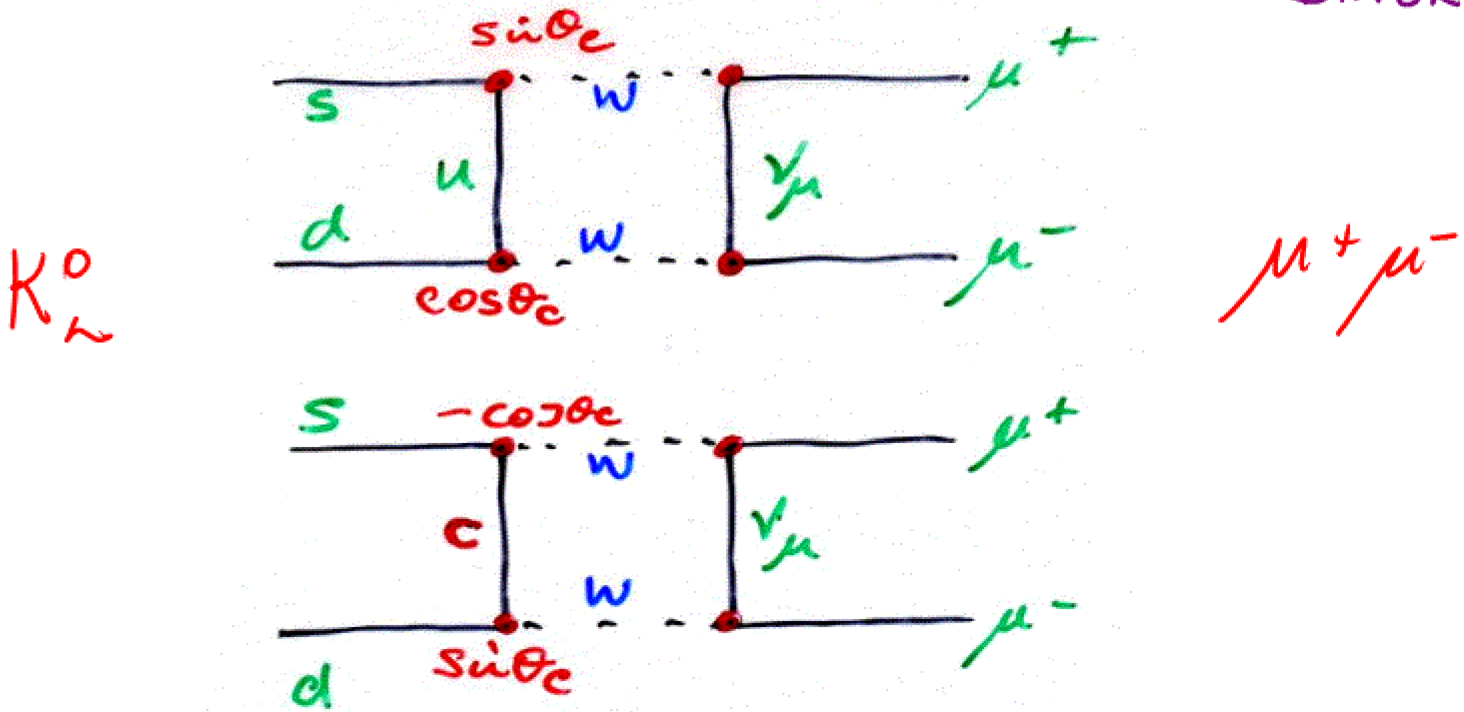
$s\cos\theta - d\sin\theta$



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

GIM MECHANISM PREDICTED m_{CHARM}

FOR $K^0_L \to \mu^+\mu^-$ 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 $\to$ $m_c \approx 1.5\ \mathrm{GeV}/c^2$ ✓

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

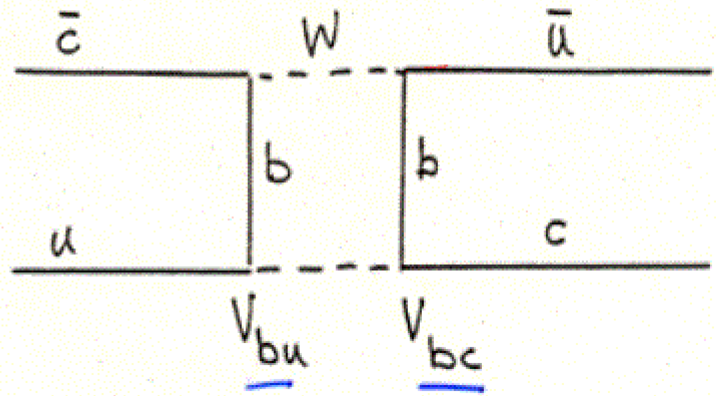
$m_c \rightarrow$ K DECAYS

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

$m_H \rightarrow$ RADIATIVE CORRECTIONS

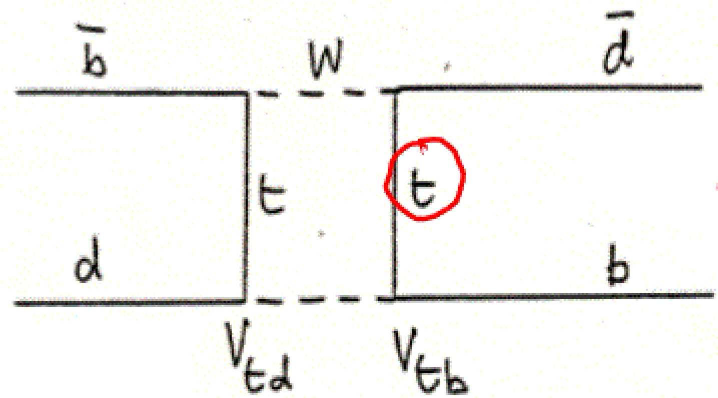
RARE DECAYS CAN ACCESS HIGHER MASS SCALES THAN DIRECT PRODUCTION AT ACCELERATORS

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



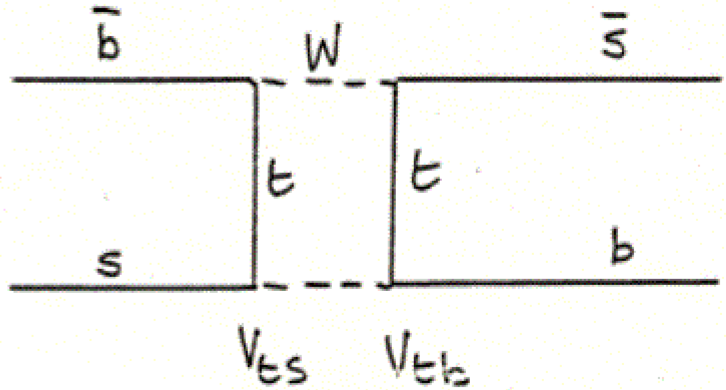
$B^0_d \bar{B}^0_d$

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



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

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



CABIBBO – KOBAYASHI – MASKAWA MATRIX

FOR 3 GENERATIONS OF QUARK – GENERALIZE THE CABIBBO FLAVOUR MIXING MATRIX.

WEAK EIGENSTATES $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$ COLOUR EIGENSTATES

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

$V_{ab} \rightarrow$ STRENGTH OF TRANSITION $a \rightarrow b$

$V_{ud} \sim \cos\theta_c$

$V_{us} \sim \sin\theta_c$

MOST GENERAL 3x3 MATRIX

$$\begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{pmatrix}$$

9 COMPLEX ELEMENTS

→ 18 REAL NUMBERS

THIS MATRIX MUST BE UNITARY — PRESERVE PROBABILITY

$$V^{+}_{\alpha\beta} V_{\beta\gamma} = \delta_{\alpha\gamma} \rightarrow (\quad)^{+}(\quad) = \begin{pmatrix} 1 & & 0 \\ & \ddots & \\ 0 & & 1 \end{pmatrix}$$

eg $V_{11}^{+} V_{11} + V_{12}^{+} V_{21} + V_{13}^{+} V_{31} = 1$

$V_{11}^{+} V_{12} + V_{12}^{+} V_{22} + V_{13}^{+} V_{32} = 0$

OF PARAMETERS

FOR 2x2 → 4 CONSTRAINT EQUATIONS $8 \rightarrow 4$

FOR 3x3 → 9 CONSTRAINT EQUATIONS $18 - 9$

GENERALLY $N \times N \longrightarrow 2N^2$ REAL PARAMETERS

UNITARITY REDUCES $2N^2 \rightarrow N^2$ REAL PARAMETERS

RECALL CABIBBO MATRIX - WRITE AS

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} e^{i\gamma} & e^{i\beta} \\ e^{i\delta} & e^{i\gamma} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

THESE ARE ACTUALLY WAVE FUNCTIONS COMPLEX NUMBERS

EACH ELEMENT DEPENDS ON ONLY ONE PARAMETER

CAN ABSORB A PHASE INTO EACH QUARK WAVE FN.

$d \rightarrow d e^{i\theta_1}$, $d' \rightarrow d' e^{i\theta_2}$ CHANGES NOTHING $[\psi\psi^*]$

ABSORB ALL 4 PHASES ? $\rightarrow$ NO, SINCE $V \equiv V e^{i\phi}$

$\therefore$ ONE DEGREE OF FREEDOM (ONE PARAMETER)

CALL IT "θ_c"

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

$N \times N$ MATRIX $\rightarrow$ $2N^2$ REAL PARAMETERS

$\downarrow$ UNITARITY

N^2 REAL PARAMETERS

ABSORB PHASES INTO QUARK WAVE FUNCTIONS

NUMBER OF GENERATIONS

$(2N-1)$ ABSORBED

NOW HAVE $N^2 - (2N-1) = (N-1)^2$ REAL PARAMETERS IN THE MATRIX

$N=2 \Rightarrow$ ONE REAL PARAMETER

2×2 IS A VERY SPECIAL CASE

LET'S LOOK AT 3×3

CONSIDER CASE WHEN HAVE REAL $N \times N$ MATRIX

REAL UNITARY MATRIX $\rightarrow$ ORTHOGONAL MATRIX

$$A\tilde{A} = 1$$

eg. $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \rightarrow \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} a & c \\ b & d \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$a^2 + b^2 = 1$ REMOVES ONE PARAMETER

$c^2 + d^2 = 1$ "

$ac = -db$ "

$2 \times 2 \Rightarrow 4 - 3 = 1$

GENERALLY $\frac{N}{2}(N-1)$ INDEPENDANT REAL PARAMETERS

PUTTING THE WHOLE ARGUMENT TOGETHER

- $N \times N$ COMPLEX UNITARY MATRIX

  $(N-1)^2$ INDEPENDENT PARAMETERS

- OF THESE $\frac{N}{2}(N-1)$ ARE REAL

- SO THERE ARE

$$(N-1)^2 - \frac{N}{2}(N-1) = \frac{(N-1)(N-2)}{2}$$

REMAINING COMPLEX NUMBERS OR PHASES

- N x N GENERAL MATRIX ← UNITARY

COMPLEX ELEMENTS

$$\frac{N(N-1)}{2}$$ REAL PARAMETERS

$$\frac{(N-1)(N-2)}{2}$$ PHASES

- 2 GENERATIONS — 1 REAL PARAMETER θ_c
  0 PHASES

- 3 GENERATIONS — 3 PARAMETERS θ_1 θ_2 θ_3
  1 PHASE δ

THIS IS THE INTERESTING THING

CKM - MATRIX

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

eg $c_{12} = \cos\theta_{12}$, $s_{23} \equiv \sin\theta_{23}$ $\quad \theta_{ij} \to$ SMALL

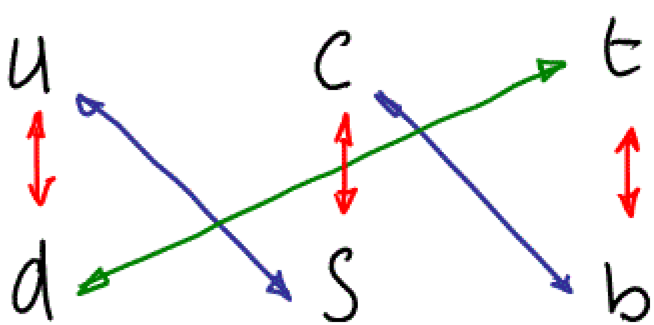
EXPERIMENTALLY $$V \approx \begin{pmatrix} 1 & s_{12} & s_{13}e^{i\delta} \\ -s_{12} & 1 & s_{23} \\ -s_{13}e^{i\delta} & -s_{23} & 1 \end{pmatrix}$$

θ_{12} = CABIBBO ANGLE

RED >> BLUE >> GREEN

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\text{EXPERIMENT} \longrightarrow \begin{pmatrix} 0.975 & 0.22 & 0.003 \\ -0.22 & 0.974 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$



THE CLOSER QUARKS ARE IN THE GENERATION PATTER $\rightarrow$ THE MORE PROBABLE ARE TRANSITIONS

CKM - MATRIX

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

WEAK EIGENSTATES

MASS EIGENSTATES

WEAK CHARGED CURRENT VERTICES ARE:

$$-i \frac{g_W}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \gamma^\mu \frac{1}{2}(1-\gamma^5) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

ADJOINT

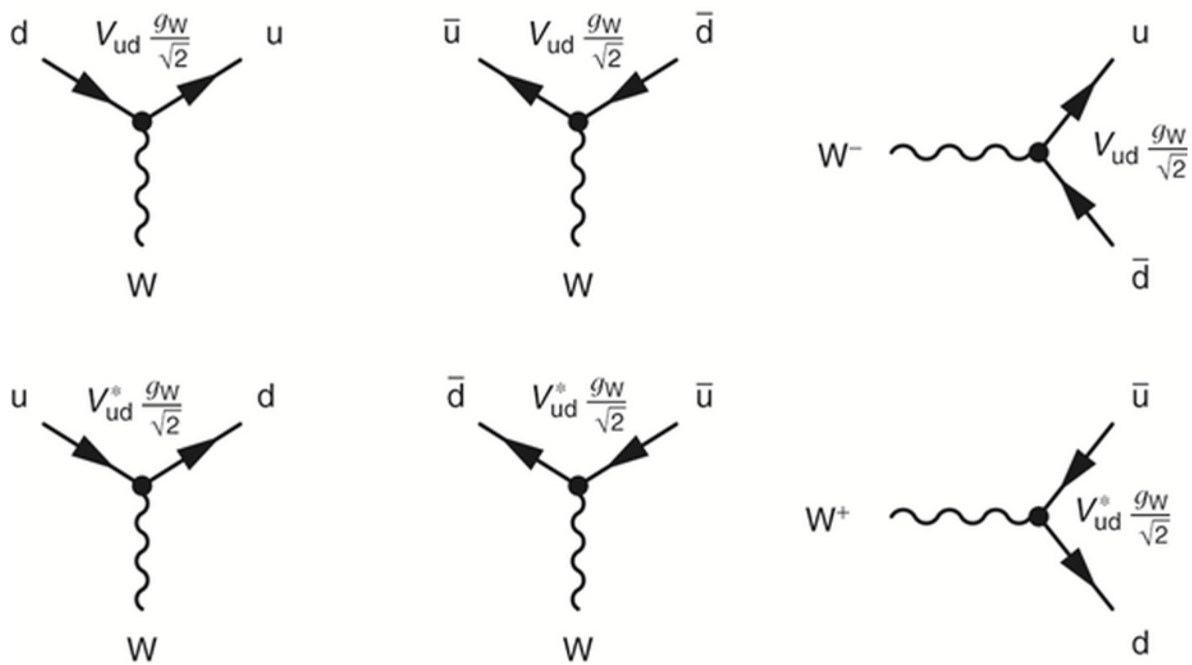
u SPINOR

RELATIVE STRENGTH OF

INTERACTION VERTEX DETERMINED

BY V_{xy}

$W \rightleftharpoons ud$ VERTEX



$$J^{\mu}_{du} = i\frac{g_W}{\sqrt{2}} V_{ud}\, \bar{u}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)\, d$$

V_{ud} WHEN $-\frac{1}{3}$ QUARK IS SPINOR

V_{ud}^* WHEN $-\frac{1}{3}$ QUARK IS ADJOINT SPINOR

IF CKM MATRIX WERE REAL, IT WOULD DESCRIBE 3 ORTHOGONAL ROTATIONS

GENERATION
$2 \leftrightarrow 3$
$1 \leftrightarrow 3$
$1 \leftrightarrow 2$

COSINE θ_{13}

$\sin\theta_{12}$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

UNITARY 3x3 MATRIX $VV^{+} = I \rightarrow 9$ CONSTRAINTS

ELEMENTS COMPLEX $\rightarrow$ 6 DEGREES OF FREEDOM

EACH APPEARS AS COMPLEX PHASE $e^{i\delta}$

$\hookrightarrow$ BUT NOT ALL PHASES PHYSICALLY RELEVANT

$$i\frac{g_W}{\sqrt{2}}(\bar{u},\bar{c},\bar{t})\gamma^\mu\tfrac{1}{2}(1-\gamma^5)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb}\end{pmatrix}\begin{pmatrix} d \\ s \\ b\end{pmatrix}$$

THESE 4-VECTOR CURRENTS UNCHANGED BY XFORM

$$\bar{q}_\alpha \to \bar{q}_\alpha e^{i\theta_\alpha},\quad q_k \to q_k e^{i\theta_k};\quad V_{\alpha k} \to V_{\alpha k} e^{i(\bar{q}_\alpha - q_k)}$$

$\bar{q}_\alpha \to \bar{u}, \bar{c}, \bar{t}$

ABSORB ALL SIX COMPLEX PHASES INTO QUARK WAVE FUNCTIONS?

NO! OVERALL PHASE $\longrightarrow$ NO PHYSICAL CONSEQUENCE

DEFINE ALL SIX PHASES RELATIVE TO PHASE OF ARBITRARILY CHOSEN WAVE FN.

$$\bar{q}_\alpha \to \bar{q}_\alpha e^{i(\theta+\theta'_\alpha)},\quad q_k \to q_k e^{i(\theta+\theta'_k)};\quad V_{\alpha k} \to V_{\alpha k} e^{i(\theta-\theta'_k)}$$

SO ONLY 5 PHASES CAN BE ABSORBED INTO WAVE FUNCTIONS $\rightarrow$ ONE PHASE REMAINS

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

QUARKS BOUND INSIDE HADRONS

↳ OBSERVE DECAYS OF HADRONS, NOT DIRECT QUARK TRANSITIONS

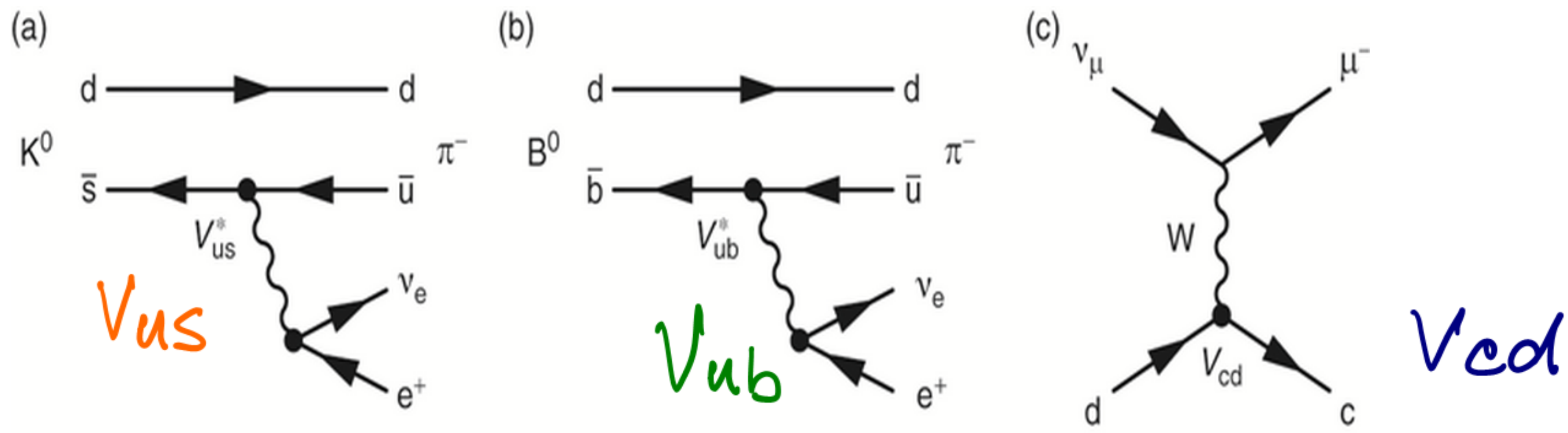
WHAT WE OBSERVE EXPERIMENTALLY ARE THE QUARK MASS EIGENSTATES

$$|\text{WEAK}\rangle = (V) \times |\text{MASS}\rangle$$

BY EXPERIMENTALLY OBSERVING HADRONIC DECAYS → WE CAN MEASURE THE ELEMENTS OF THE CKM MATRIX

ALREADY NOTED THAT V_{ud} IS MEASURED IN NUCLEAR β-DECAYS

$$|V_{ud}| = \cos\theta_c = 0.97425(22)$$



$V_{us} \rightarrow \quad K^0 \rightarrow \pi^- e^+ \nu_e$

us

$|V_{us}| = 0.2252(9)$

$V_{ub} \rightarrow \quad B^0 \rightarrow \pi^- e^+ \nu_e$

$d\bar{b}$

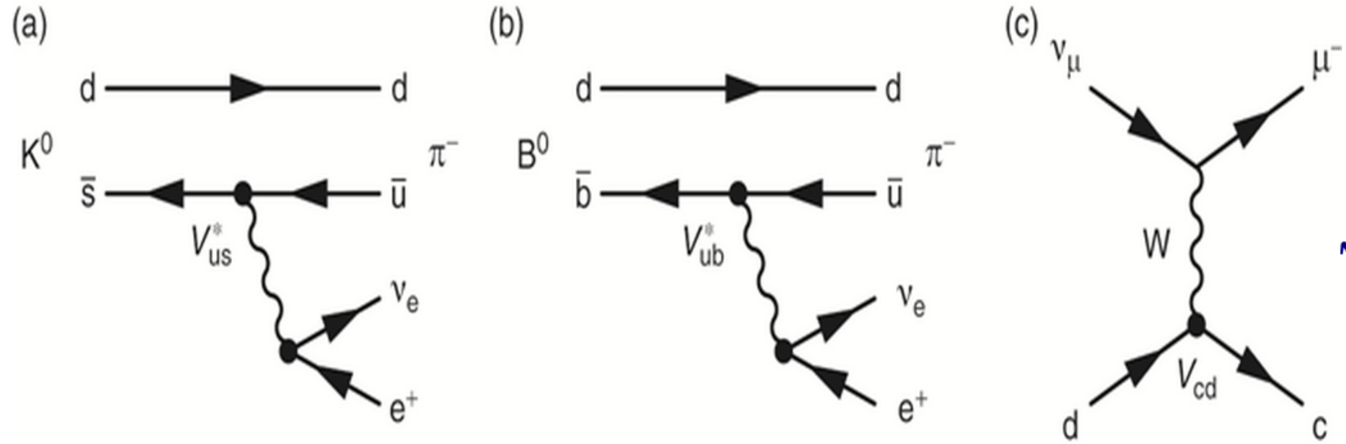
$|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$

$V_{cs} \rightarrow \quad D^+ \rightarrow \mu^+ \nu_\mu$

$c\bar{s}$

$|V_{cs}| = 1.006 \pm 0.023$

$|V_{cb}| = (40.9 \pm 1.1) \times 10^{-3}$



V_{cd}

V_{cd} $\quad \nu_\mu d \rightarrow \mu^- c$

$\nu_\mu p \rightarrow \mu^- D^+$ EXPERIMENTALLY

$\qquad\qquad\quad \hookrightarrow \mu^+ \nu_\mu$

OPPOSITE SIGN DIMUONS

$|V_{cd}| = 0.230\,(11)$

Observation of New-Particle Production by High-Energy Neutrinos and Antineutrinos*

A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, F. Messing, R. Orr, D. D. Reeder, C. Rubbia, R. Stefanski, L. Sulak, and P. Wanderer

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(Received 13 January 1975)

We have observed fourteen events in which two muons are produced by high-energy neutrino and antineutrino interactions. The absence of trimuon events and the observed characteristics of the dimuon events require the existence of one or more new massive particles that decay through the weak interaction. The new particle mass is estimated to lie between 2 and 4 GeV.

We have previously reported two candidates for dimuon production by neutrinos.[1] Subsequently, twelve additional events have been observed and are reported here. The characteristics of production, which will be discussed in greater detail later,[2] are consistent with a new particle of mass less than or near 4 GeV. Evidence against the decays of charged pions and kaons as the source of the second muon is provided by (i) the rate of dimuon events, (ii) the opposite signs of their electric charges, (iii) the different densities of the target materials in which they were produced, and (iv) the distributions in muon momentum and transverse momentum.

The experimental method makes use of several features of the liquid-scintillator calorimeter, magnetic-spectrometer detector previously reported.[3,4] Events produced either in the liquid or in a block of iron, with two particles in time coincidence which penetrate at least 1.2 m of iron, are selected. One such event is shown in Fig. 1. The momentum and angle of each muon is measured and extrapolated back into the target. The longitudinal position at which an interaction in the calorimeter occurs can also be determined by the pulse-height distribution in the calorimeter. The distance of approach Δ of the two rays at the approximate longitudinal position of the interaction that triggered the event was obtained for every dimuon candidate. The distribution is shown in Fig. 2(a). Two further requirements were made on the sample: (i) The vertex of the event defined as the (x, y, z) position at the dis-

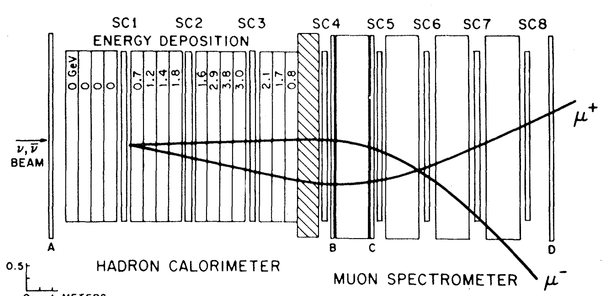


FIG. 1. Sketch of a muon-pair event which starts in module 5 of the ionization calorimeter and deposits 21.8 GeV ionization energy. The muon momenta are $p_{\mu^+} = 14.7$ GeV and $p_{\mu^-} = 8.4$ GeV.

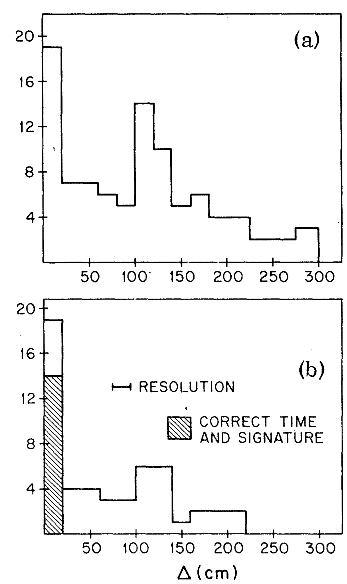
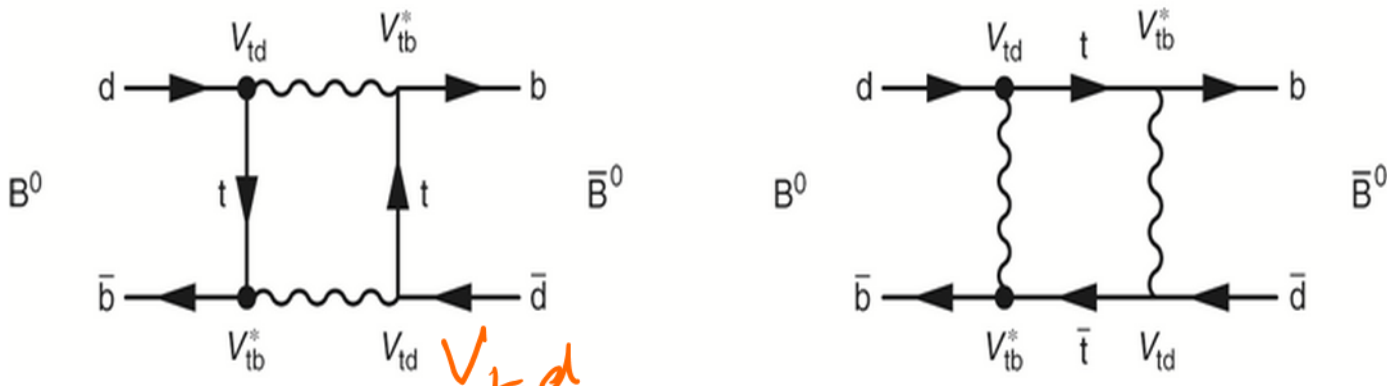
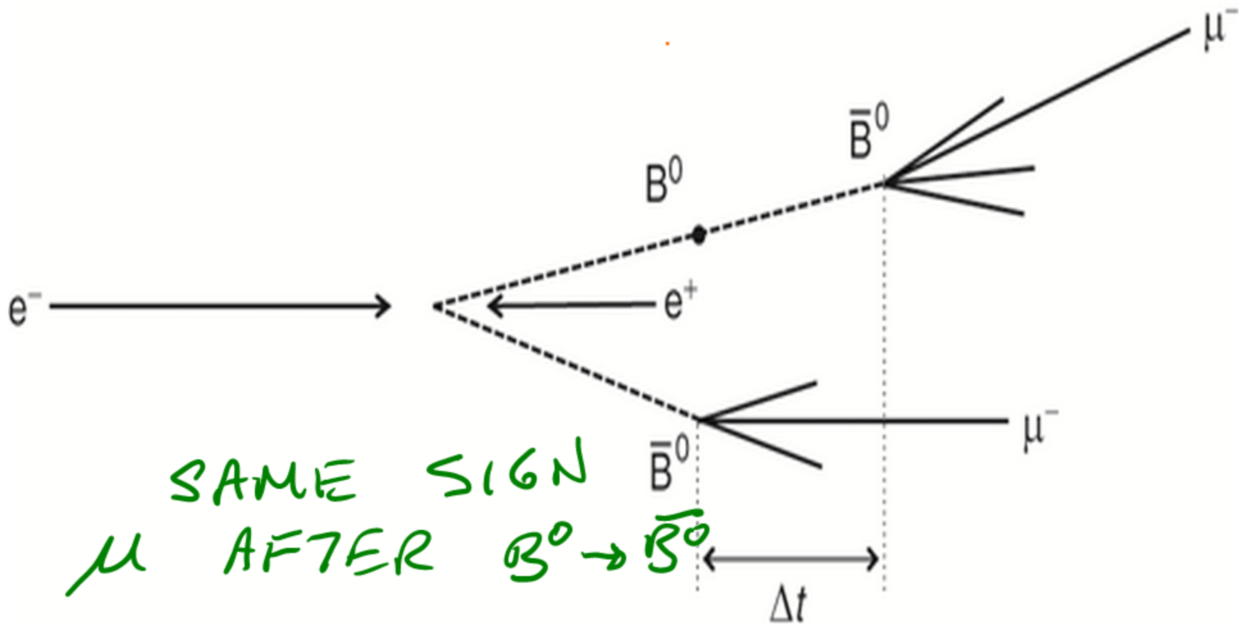


FIG. 2. (a) The distribution in the distance between the extrapolated muon tracks at the z position where an interaction occurred. (b) The distance between the extrapolated muon tracks after the muons were required (i) to have the correct timing, (ii) to have a track configuration with vertex inside the target, and (iii) to traverse the correct counter hodoscope units. The accepted events are cross hatched.



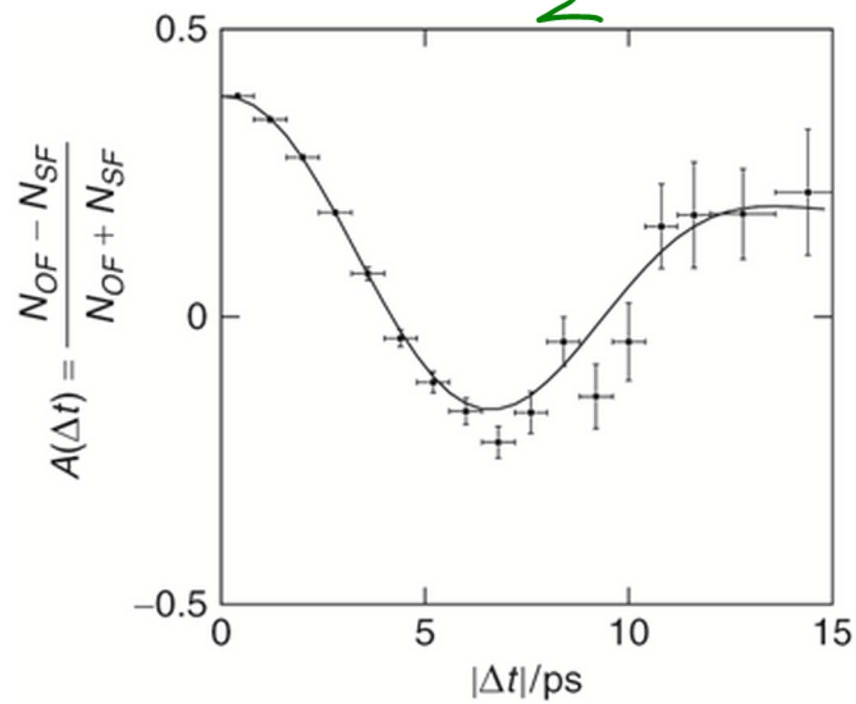
V_{tb} V_{td}



SAME SIGN

μ AFTER $B^0 \to \bar{B}^0$

$$\frac{\mu^+\mu^- - \mu^{\mp}\mp}{\Sigma}$$



$$|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}$$

$$|V_{ts}| = (42.9 \pm 2.6) \times 10^{-3}$$

OFF DIAGONAL ELEMENTS SMALL, SO CAN EXPRESS CKM AS EXPANSION IN

$$\lambda = \sin\theta_c = 0.225$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda, A, \rho, \eta \rightarrow$ REAL PARAMETERS

WE WILL COME BACK TO THIS!