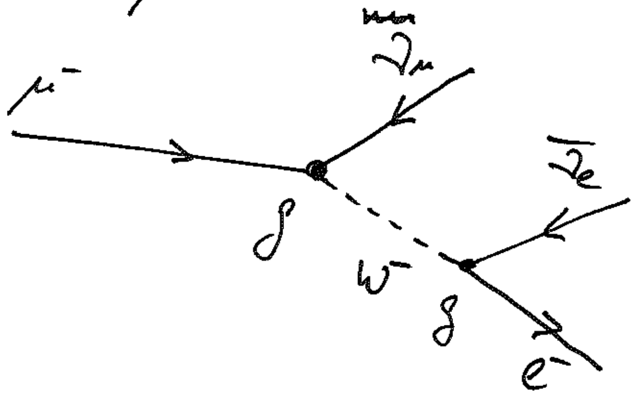
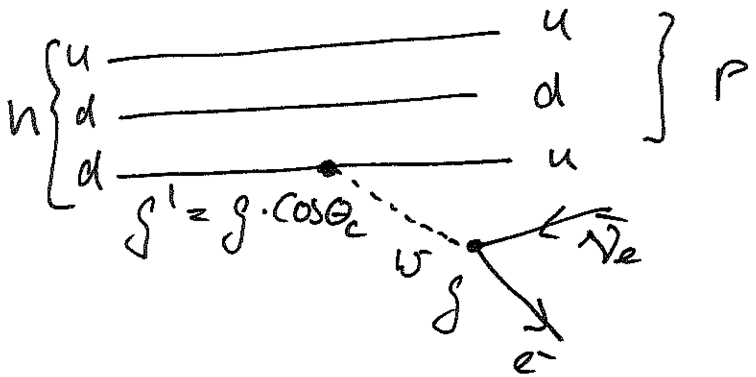
Schwache Zerfälle von Quarks: Cabibbo Mischung

Fermikonstante G aus β^--Zerfällen bestimmen => ~4% kleiner als aus μ-Zerfall



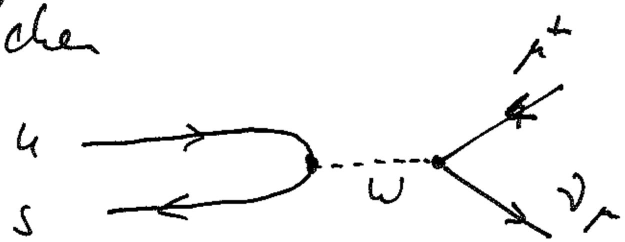
$M \propto g^2$



$M \propto g^2 \cos\Theta_c$

Semileptonische Zerfälle von seltsamen Teilchen

z. Bsp: $K^+ \rightarrow \mu^+ \nu_\mu$



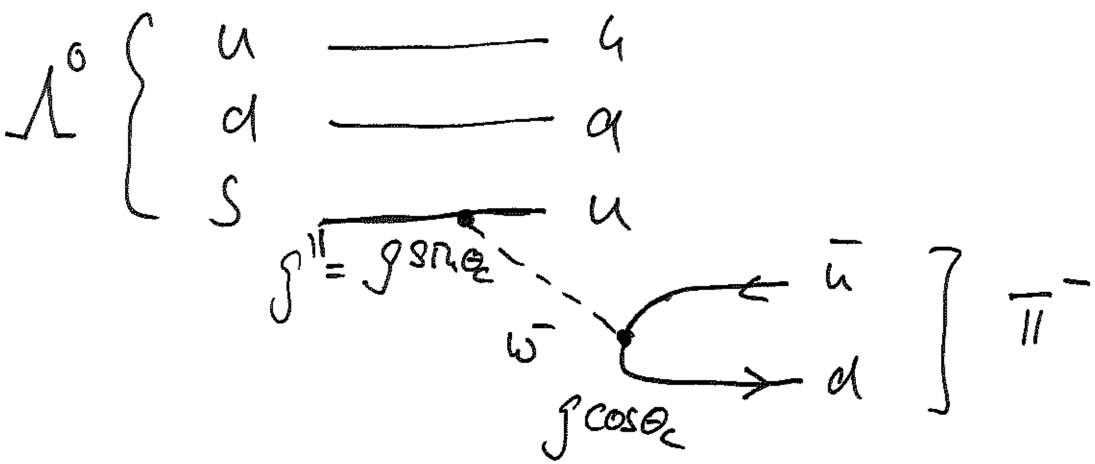
$\underset{dds}{\Sigma^-} \rightarrow n\, e^- \bar{\nu}_e$

$\Delta S = 1$

zeigen eine Unterdrückungsfaktor ~ 20 verglich
mit Zerfällen mit $\Delta S = 0$

z. Bsp $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

$n \rightarrow p e^- \bar{\nu}_e$



$$M \propto g^2 \cos\theta_c \sin\theta_c$$

Nicola Cabibbo (1963)

d und s sind keine Eigenzustände der schw. WW!

Eigenzustände d. schw. WW sind gemischte („gedrehte") Zustände

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

1960's

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

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$$

Cabibbo Angle
(Flavor mixing

flavor Weak state

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

flavor Mass eigenstate

Doublets: Leptonen $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$

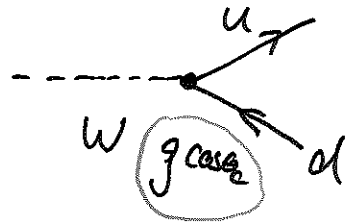
Quarks $\begin{pmatrix} u \\ d \cos\Theta_C + s \sin\Theta_C \end{pmatrix}_L$

N.B. 1963 waren nur u, d, s Quarks bekannt

N.B.: Kopplungskonstante G der Dubletts identisch für Leptonen und für Quarks

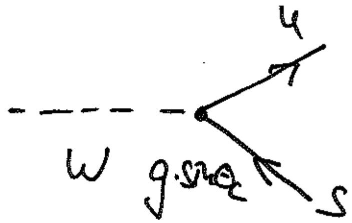
für $\Delta S = 0$: (π^-, n-decays) haben effektive Kopplungskonstante

$G \cdot \cos\Theta_C$



Cabibbo „erlaubt"

für $\Delta S = 1$: $G \cdot \sin\Theta_C$

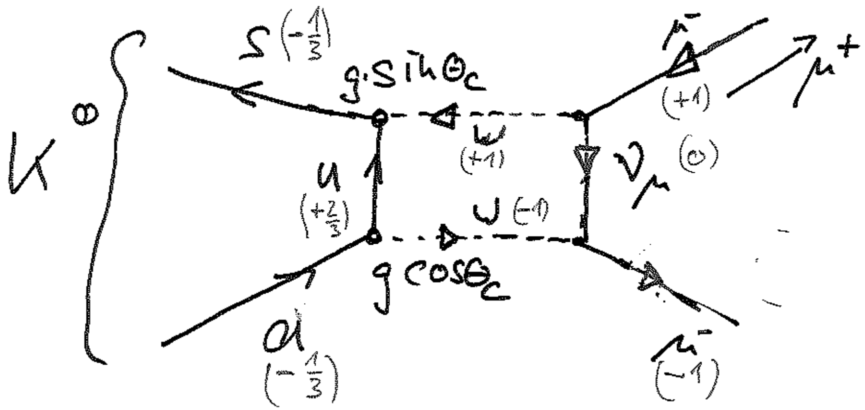


Cabibbo „unterdrückt"

Experiment: $\Theta_C \simeq 12^\circ$

GIM Unterdrückung: Vorhersage des c-Quarks

$$\frac{\Gamma(K_L^0 \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \text{all modes})} = (9.1 \pm 1.9) \cdot 10^{-9}$$

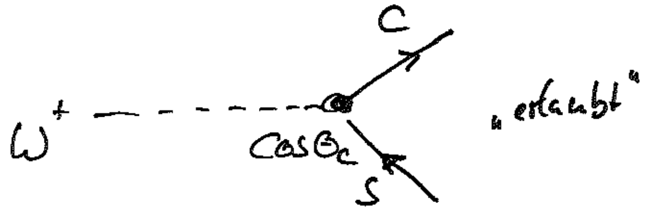


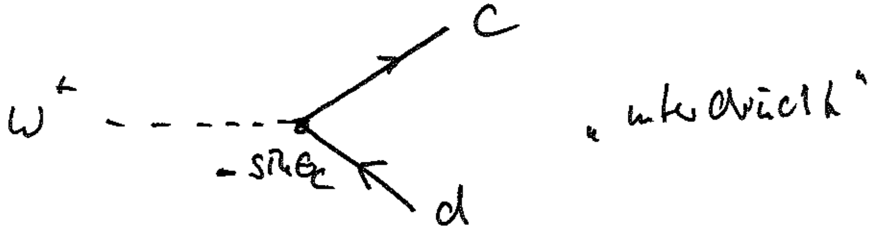
$$\begin{pmatrix} u \\ d\cos\Theta_c + s\sin\Theta_c \end{pmatrix}$$

$$M \propto \cos\Theta_c \sin\Theta_c$$

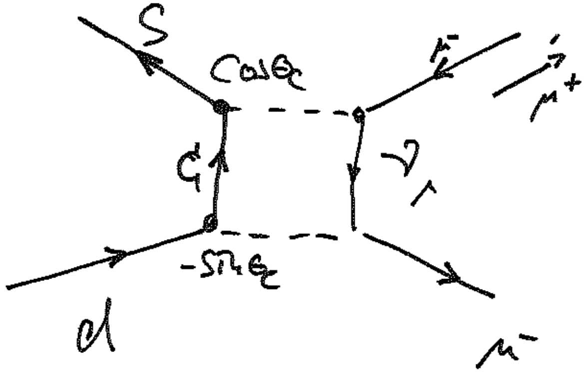
Unter Annahme von 3 Quarks (u, d, s) ist die erwartete Rate weit größer als gemessene Rate

Glashow, Iliopoulos, Maiani (GIM) schlagen Existenz eines weiteren Quarks c (charm) vor $\Rightarrow$ Cabibbo-GIM Schema





Weitere



$$\begin{pmatrix} c \\ d(-\sin\theta_c) + s\cos\theta_c \end{pmatrix}$$

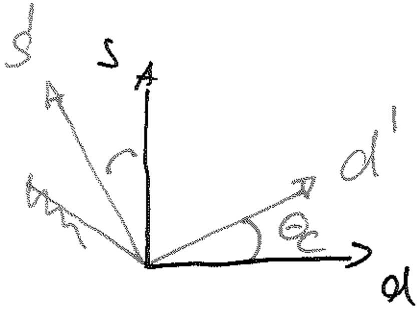
$$M \propto -\sin\theta_c \cos\theta_c$$

Beide Diagramme würden sich komplett aufheben, wäre nicht die Massendifferenz zw. u und c

$$\sim g^4 (m_c^2 - m_u^2) / m_W^2$$

Linkshändige Dubletts die an ~~Bet~~ die schwache WW. (geladener Strom) teilnehmen

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$$



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

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

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

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

Eigenzustände d. schw. WW ↑

← EZ d. st. WW

Eigenzustände der schw. WW (d', s') sind <u>nicht</u> identisch mit den Masseneigenzuständen (d, s) (besser: EZ. der starken WW)

Erweiterung auf
3 Quark Familien (1972) Cabibbo – Kobayashi – Maskawa)
CKM – Mischung

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

<u>Unitarität</u>

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V^+ V = 1$$

V ist <u>unitäre</u> $N \times N$ Matrix
$N(N-1)/2$ reelle Parameter (Euler Winkel ξ für $N=3$)
und $(N-1)(N-2)/2$ nichttriviale komplexe Phasen

The Kobayashi-Maskawa Paradigm for CP Violation

1972

Two Young Postdocs at that time !

- Proposed a "daring" explanation for CP violation in K decay:
- CP violation appears in the charged current weak interaction of quarks
- There is a single source of CP Violation $\Rightarrow$ Complex Quantum Mechanical Phase δ_{KM} in inter-quark coupling matrix
- Need at least **3 Generation of Quarks** (then not known) to facilitate this

Generations of Quarks and Leptons Circa 2002

Since then, Experiments Show

Three generations : no more, no less !

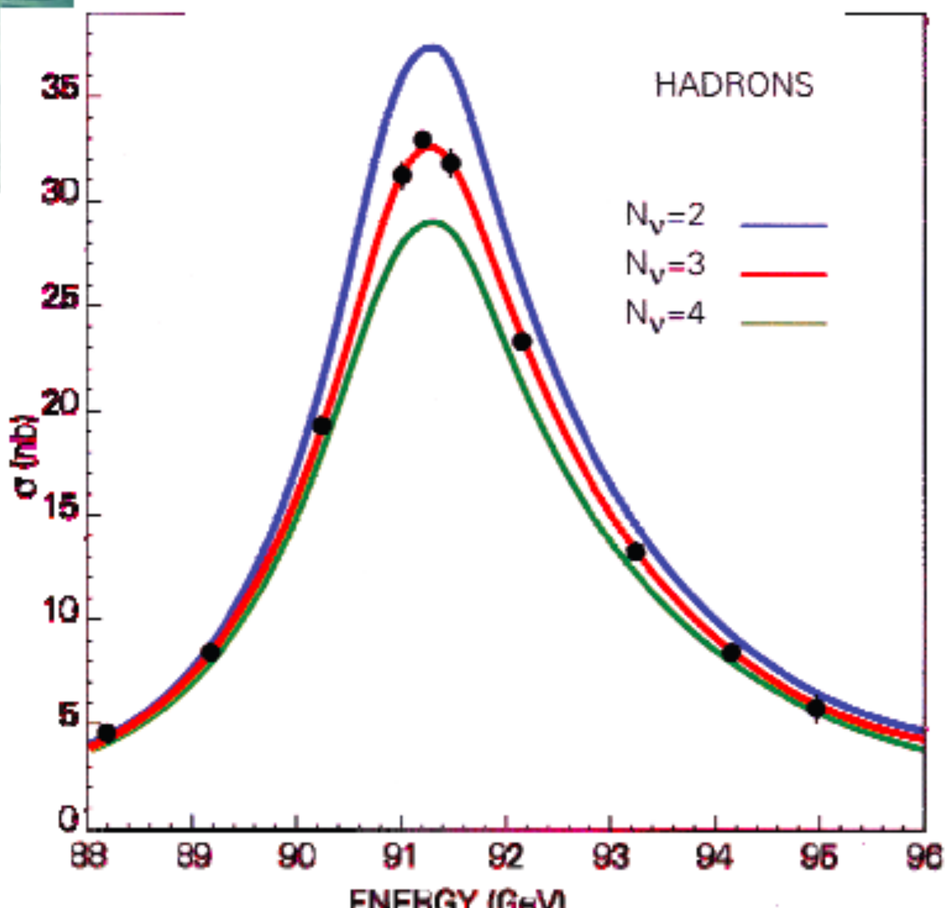
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

Just Enough to Make CP Violation Possible

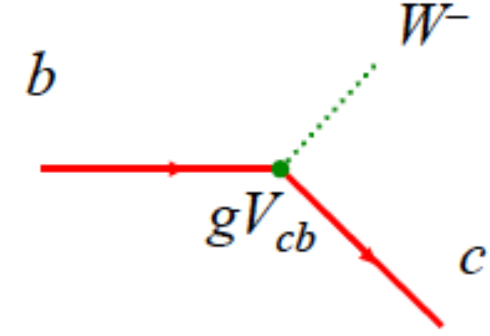
Number of Light Neutrino Families: LEP@CERN

Width of the Z resonance



The Weak Interaction Couplings of Quarks

- The coupling strength at the weak vertex is given by gV_{ij}
  - g is the universal Fermi weak coupling
  - V_{ij} depends on which quarks are involved
  - For leptons, the coupling is just g
- For 3 generations, the V_{ij} can be written as a 3x3 complex unitary matrix (CKM)
- View this matrix as rotating the quark states from a basis in which they are mass eigenstates to one in which they are Weak eigenstates



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

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

CP Violation In SM With 3 Generations

- The CKM matrix → 3×3 complex unitary matrix
- Requires 4 independent parameters to describe it:
  - 3 real numbers & 1 complex non-trivial phase
- The existence of the **complex** coupling (phase) gives rise to *CP* violation
  - If only 2 quark generations ⇒ 2×2 matrix is all real ⇒ No *CP* violation
- Some Expectations:
  - *CP* violation is the result of interference between different decay amplitudes involving weak phase
  - *CP* violation is "built" into the Standard Model with 3 generations or more …or so Kobayashi-Maskawa wondered

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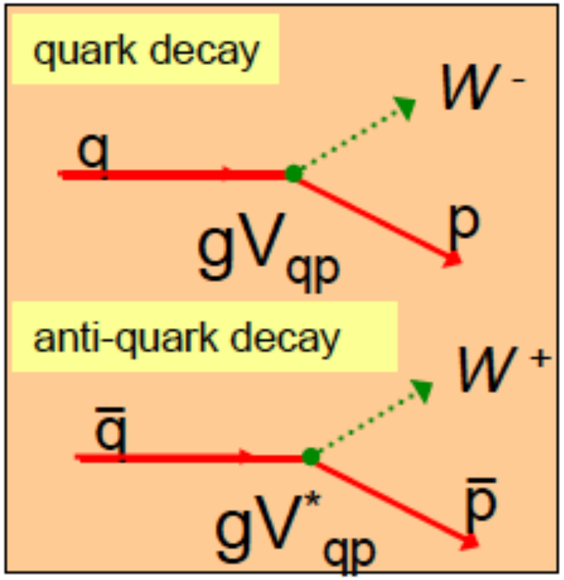

$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

Complex phases → CP violation

Cabibbo : $N=2$ => 1 reeler Winkel
0 komplexe Phase

CKM : $N=3$ => 3 reele Winkel
1 komplexer ~~Winkel~~ Phase (δ-Phase)

Phase geht in WF ein als $e^{i(\omega t + \delta)}$

Nicht invariant unter T: $t \to -t$

=> δ-Phase ermöglicht T bzw. CP Verletzung verursacht

$$T\,\psi(t) = \psi^*(-t)$$

$$e^{i(\omega t + \delta)} \xrightarrow{T} e^{-i(-\omega t + \delta)} = e^{i(\omega t - \delta)}$$