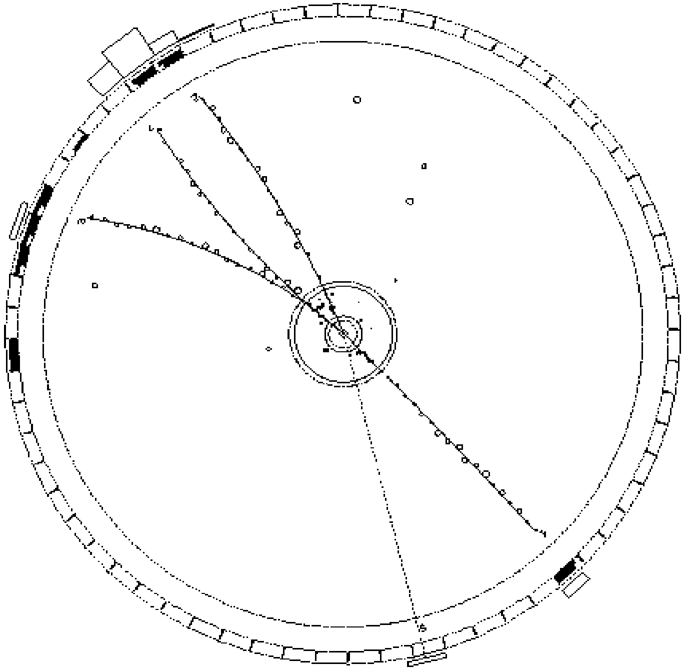
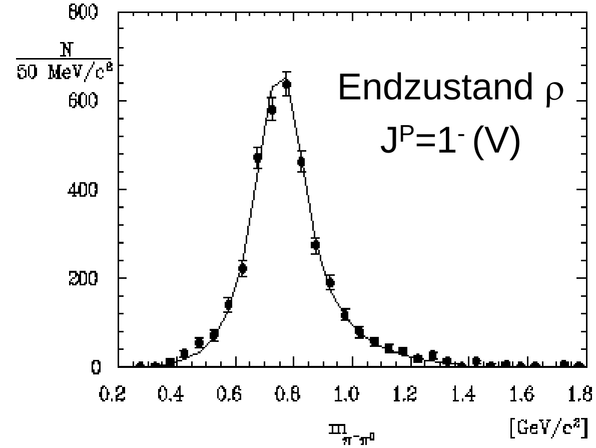
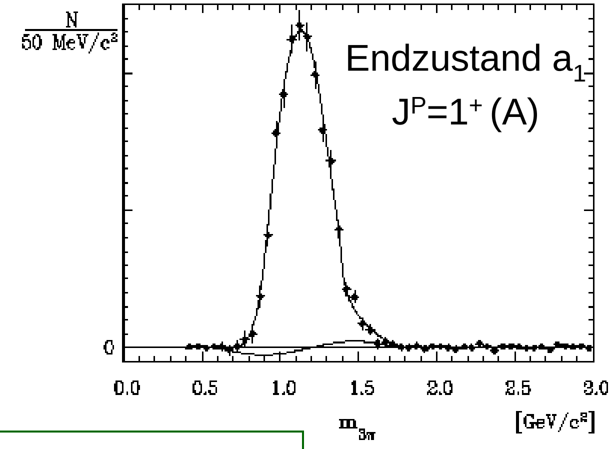
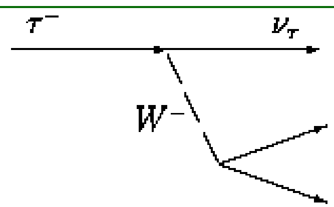
3.6 Kopplungen des W-Bosons an Quarks

Zum Beispiel: **hadronische τ-Zerfälle**







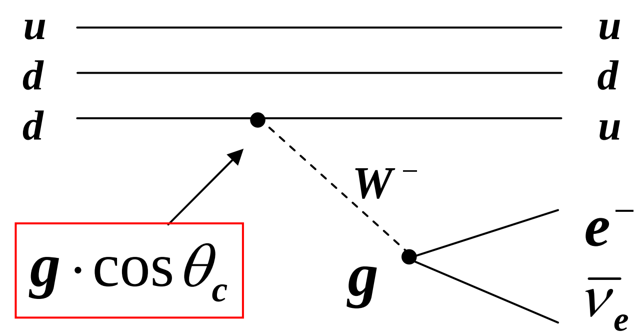


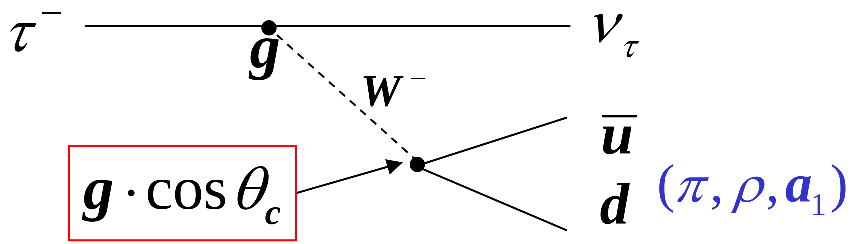
$$\begin{pmatrix} f \\ \bar{f} \end{pmatrix} = \begin{pmatrix} e^- \\ \bar{\nu}_e \end{pmatrix}, \begin{pmatrix} \mu^- \\ \bar{\nu}_\mu \end{pmatrix}, \begin{pmatrix} d \cos\theta_C + s \sin\theta_C \\ \bar{u} \end{pmatrix}$$

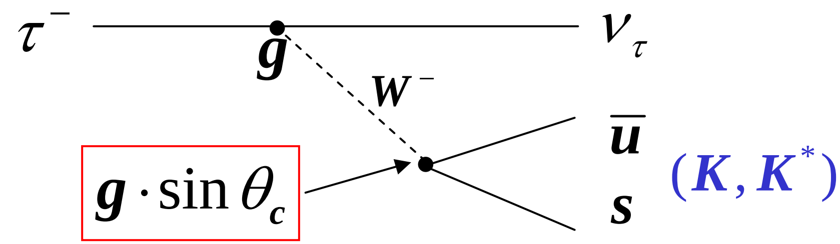
3.6.1 Flavour-Übergänge (siehe StruMa c)

β-Zerfall des Neutrons: $n \rightarrow p e^- \bar{\nu}_e$

(semileptonisch)

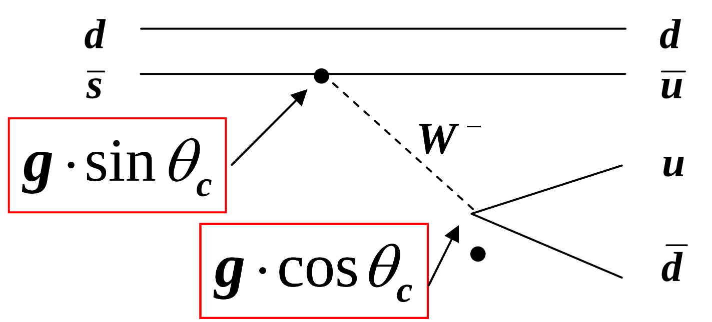






$K^0 \rightarrow \pi^+ \pi^-$

(hadronisch)



Cabibbo-Mischung (siehe StruMa c)

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

SU(2)-Dubletts:

$$\begin{pmatrix} d' \\ u \end{pmatrix} = \begin{pmatrix} \cos\theta_c\, d + \sin\theta_c\, s \\ u \end{pmatrix}$$

$$\begin{pmatrix} s' \\ c \end{pmatrix} = \begin{pmatrix} -\sin\theta_c\, d + \cos\theta_c\, s \\ c \end{pmatrix}$$

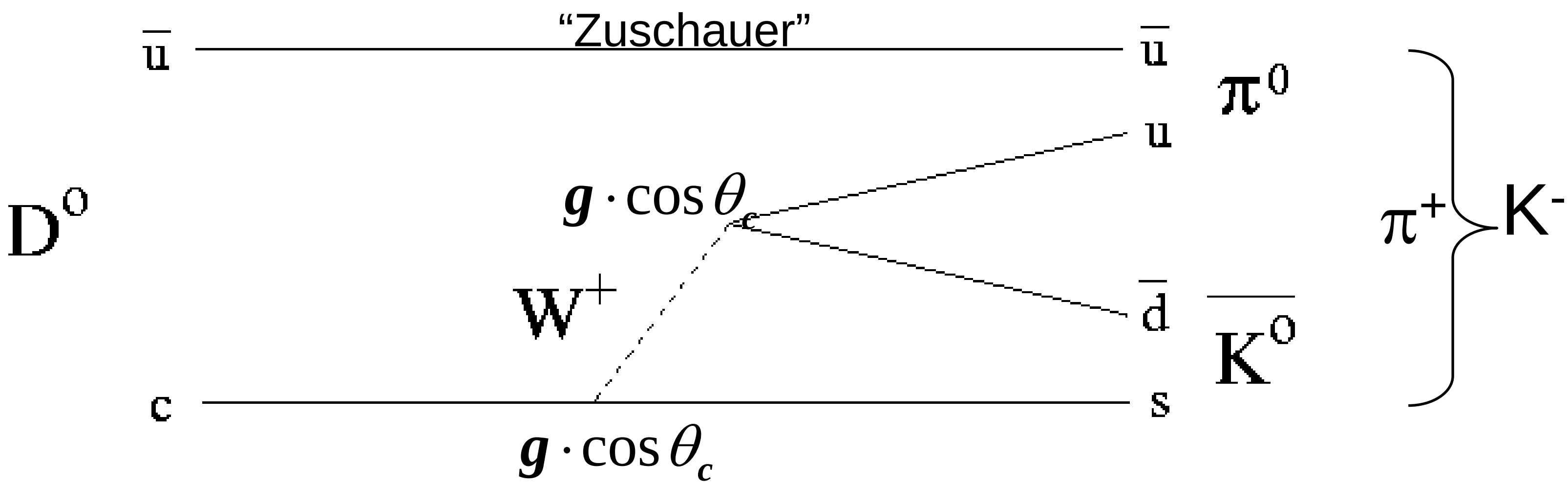
$\Rightarrow$ **Flavour-Übergänge zwischen Familien:**

$$u \to s, \quad c \to d$$

Universalität der Kopplung gilt für gemischte Quarkdubletts

Aber: Endzustände = Hadronen = definierte Flavour (starke WW) = π, ρ, *K*, ….

Cabibbo-erlaubte Zerfälle



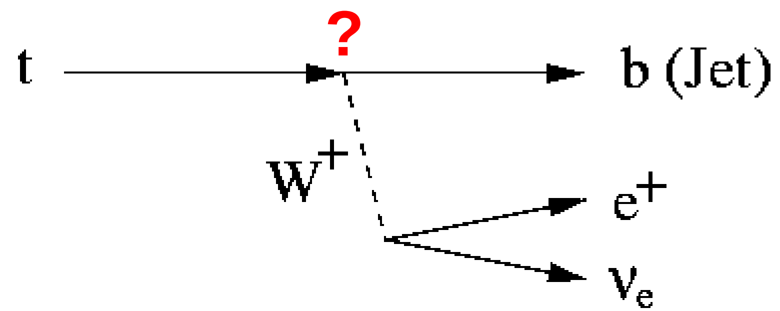
$\downarrow$

$\pi^- K^+$

doppelt
Cabibbo-unterdrückt

Exp.: $\sin\theta_c \approx 0.22, \quad \cos\theta_c \approx 0.98$

Verallgemeinerung auf 3 Generationen (CKM)



Cabibbo-Kobayashi-Maskawa-Matrix (CKM):

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

zu testen

Normierte Quarkzustände + nur 3 Generationen $\Rightarrow$ ***V* unitär (?):**

$$VV^{+} = V^{+}V = 1$$ $\Rightarrow$ 9 reelle Bed. + 5 freie Phasen

$\Rightarrow$ **CKM-Parameter: 3 Winkel + 1 Phase**

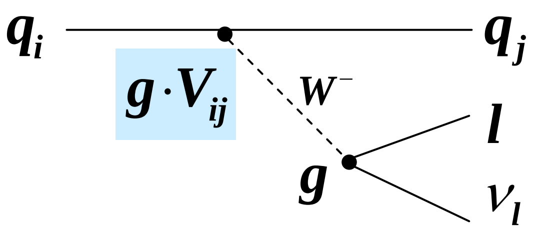
Hadronischer Strom

$$j^\mu = (\bar{u}, \bar{c}, \bar{t})\,\gamma^\mu(1-\gamma_5)\,V_{CKM}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$= \bar{u}_u\,\gamma^\mu(1-\gamma_5)\,u_d \cdot V_{ud} + \bar{u}_u\,\gamma^\mu(1-\gamma_5)\,u_s \cdot V_{us} + \ldots$$

3.6.2 Messung der CKM-Matrix

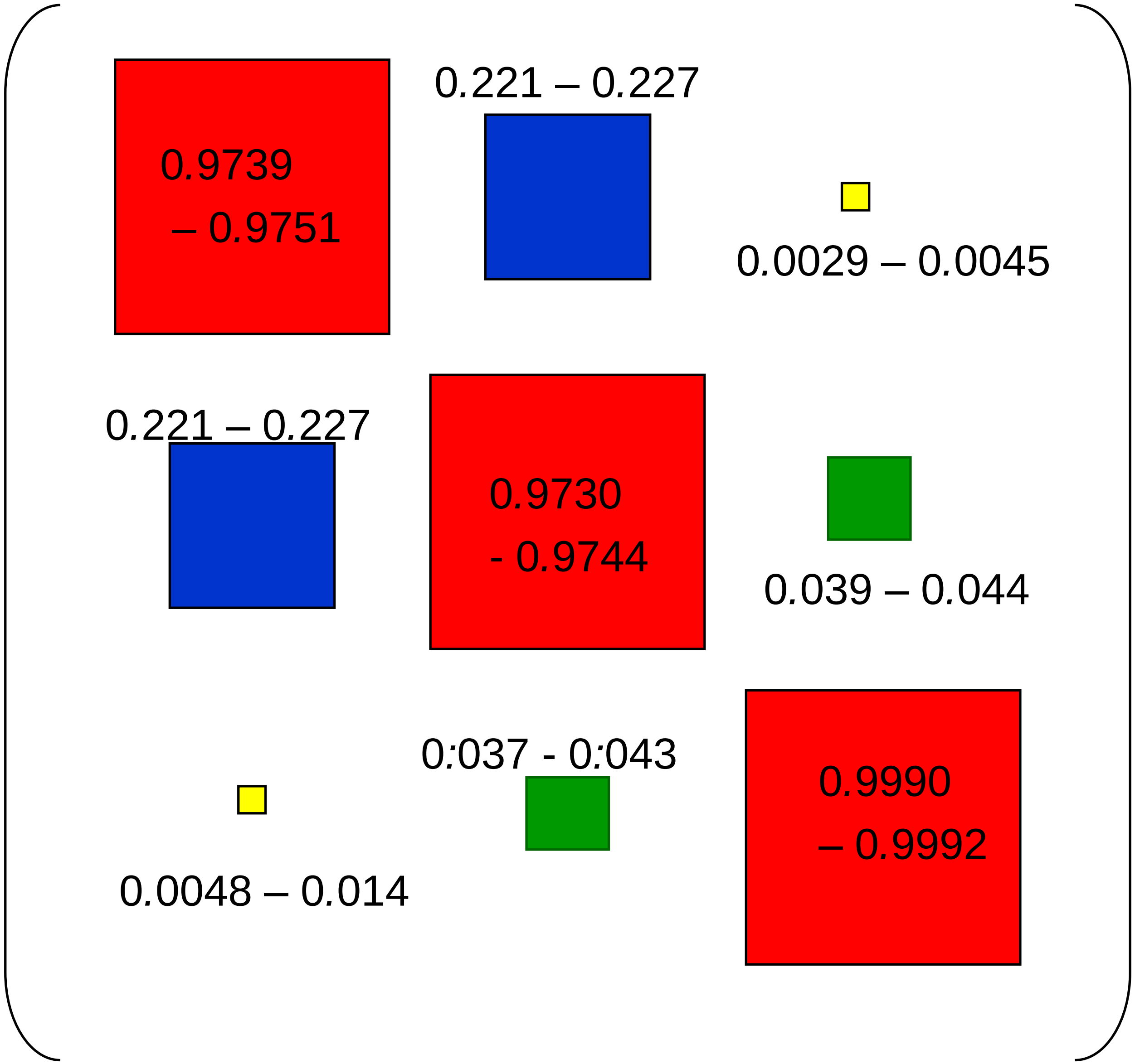
semilept. Zerfälle
+ Zuschauermodell
+ Korrekturen:



Vergleich mit μ-Zerfall ($\Rightarrow g$)

$$\Rightarrow V_{ij}$$

nahezu diagonal



Wolfenstein-Parametrisierung (s.PDG-Review)

We advocate a "standard" parametrization [3] of V that utilizes angles θ_{12}, θ_{23}, θ_{13}, and a phase, δ_{13}

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} , \qquad (11.3)$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ for the "generation" labels $i, j = 1, 2, 3$. This has

Kobayashi and Maskawa [1] originally chose a parametrization involving the four angles θ_1, θ_2, θ_3, and δ:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \qquad (11.4)$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. In the limit $\theta_2 = \theta_3 = 0$, this reduces

An approximation to the standard parametrization proposed by Wolfenstein [4] emphasizes the hierarchy in the size of the angles, $s_{12} \gg s_{23} \gg s_{13}$. Setting $\lambda \equiv s_{12}$, the sine of the Cabibbo angle, one expresses the other elements in terms of powers of λ:

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \ . \qquad (11.5)$$

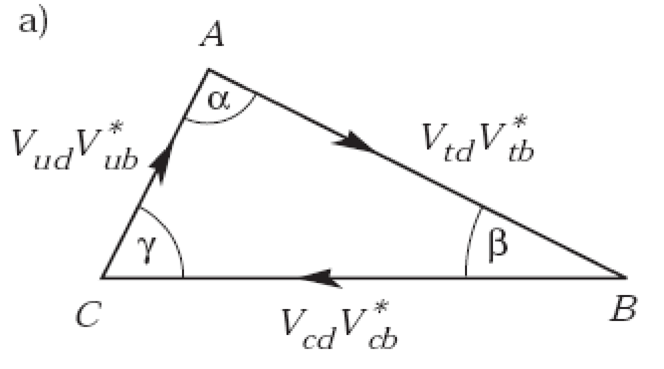
with A, ρ, and η real numbers that were intended to be of order unity. This approximate

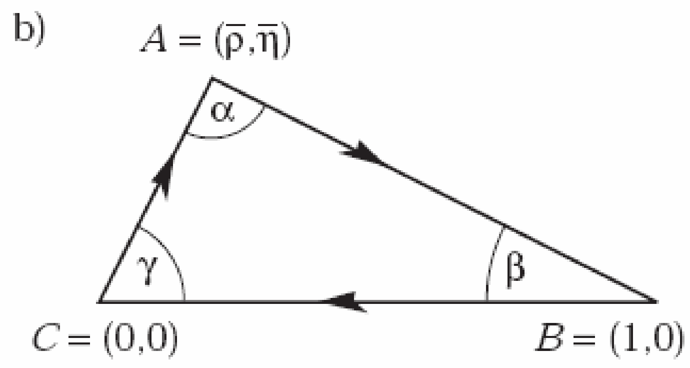
Unitaritätsdreieck

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

Unitarity applied to the first and third columns yields

$$V_{ud}\ V_{ub}^* + V_{cd}\ V_{cb}^* + V_{td}\ V_{tb}^* = 0\ .$$





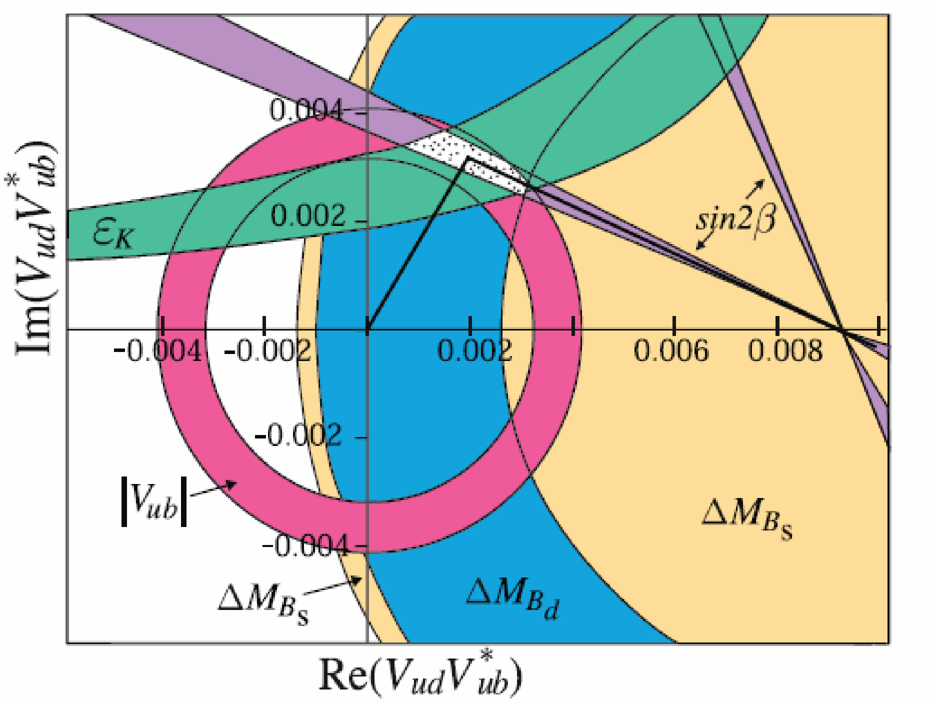
Fläche ≠ 0 ⇒ Phase ≠ 0 ⇒ CP-Verletzung:

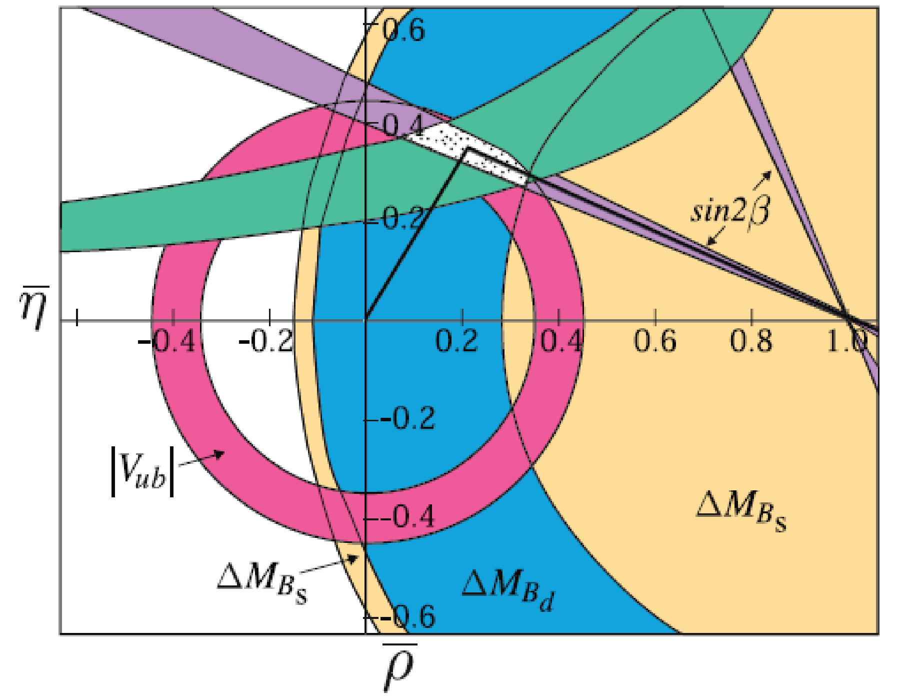
$$q_{di} \to q_{uj} \sim V_{ji}$$
$$\bar{q}_{di} \to \bar{q}_{uj} \sim V_{ji}^*$$
$$q_{uj} \to q_{di} \sim V_{ji}^*$$

CP-Verletzung (first and second lines)

T-Verletzung (first and third lines)

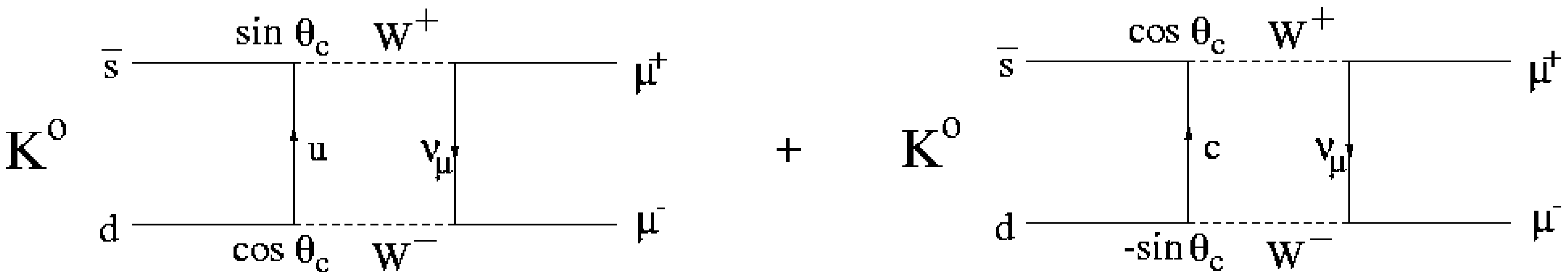
Vermessung des Unitaritätsdreiecks





$$CP=+1: \quad |K_S^0> \;\approx\; |K_1> \;=\; \frac{1}{\sqrt{2}}\left(|K^0>+|\bar{K}^0>\right) \quad (\tau = 10^{-10}\,\mathrm{s})$$

$$CP=-1: \quad |K_L^0> \;\approx\; |K_2> \;=\; \frac{1}{\sqrt{2}}\left(|K^0>-|\bar{K}^0>\right) \quad (\tau = 5\cdot 10^{-8}\,\mathrm{s})$$



$B^0\overline{B^0}$-Oszillationen