Kern- und Teilchenphysik

SS2012

Vorlesung-Website

- Johannes Blümer

KIT-Centrum Elementarteilchen- und Astroteilchenphysik KCETA

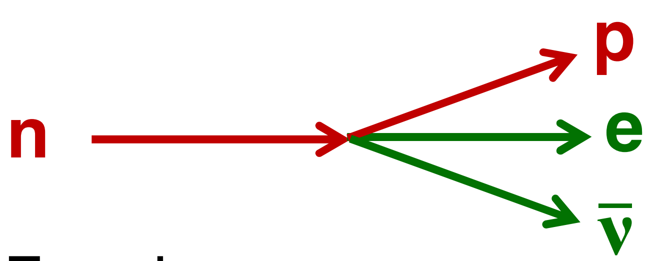
v18 26. Juni 2012 Schwache Wechselwirkung

Karlsruher Institut für Technologie

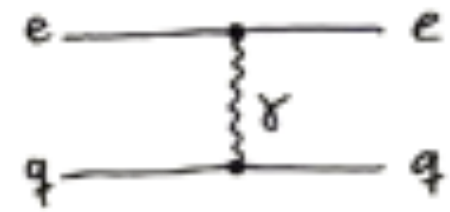
- Symmetrien und Erhaltungssätze
  - ...
  - CP-Verletzung (1)
  - CPT-Theorem
  - Symmetrieeigenschaften der 3 Wechselwirkungen
- Schwache Wechselwirkung
  - Leptonfamilien
  - geladene und neutrale Ströme
  - von der Fermitheorie zu massiven Austauschbosonen
  - Universalität der schwachen Kopplungskonstante
  - Quarkmischung: CKM-Matrix, CP-Verletzung (2)
  - Neutrino-Quark-Streuung

Erinnerung an v17

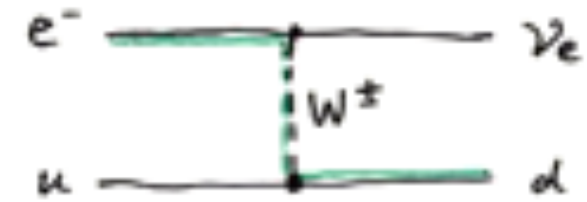
Von der Fermitheorie zu den W und Z-Bosonen



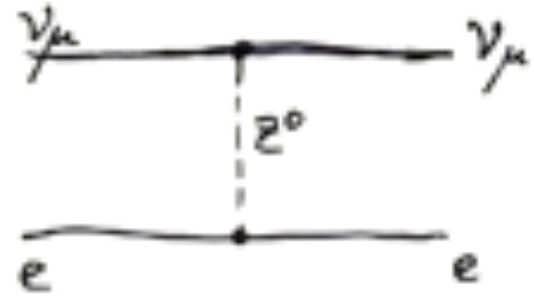
Fermi:
punktförmige 4-Fermion-Wechselwirkung



Quark-lepton-WW

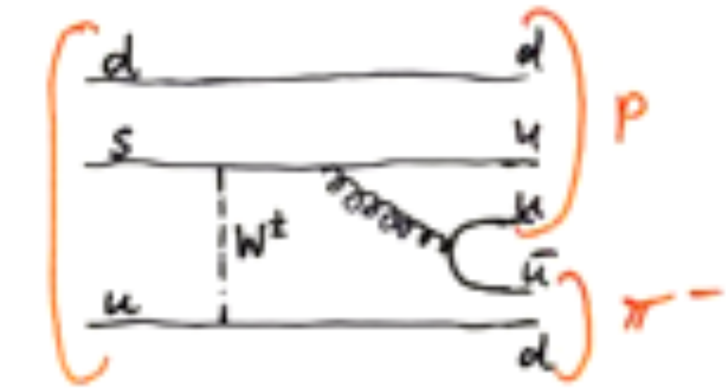


„geladener Strom" (CC)



„neutraler Strom" (NC)

elastische νe-Streuung!



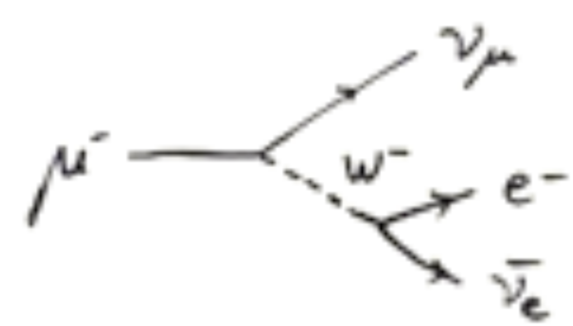
Λ-Hyperon $\Lambda^0 \to p\pi^-$

nicht-leptonischer schwacher Zerfall

W-Austausch ändert den Quarkflavour!

Universalität der schwachen Ladung?

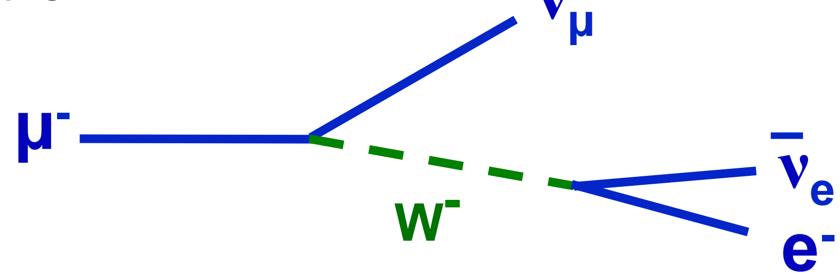
$\nu_\mu n \to \mu^- p$



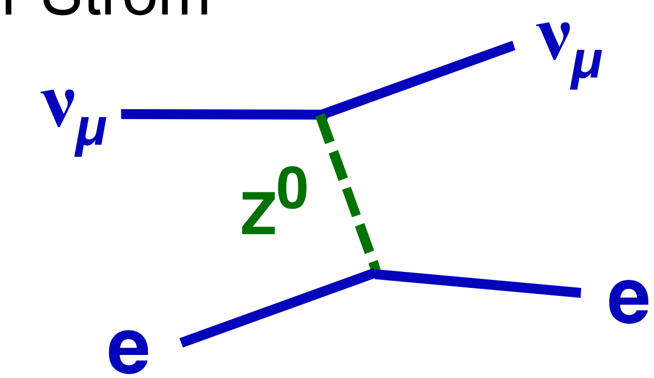
Myonzerfall

Schwache Prozesse

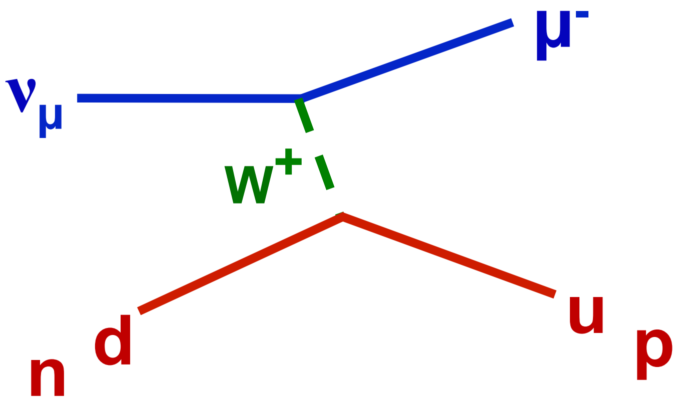
Geladener Strom

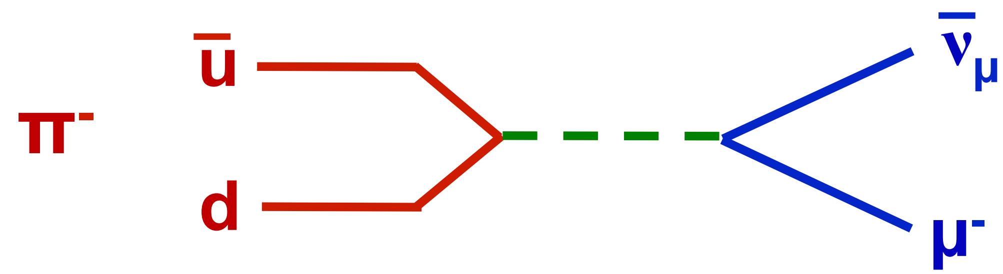


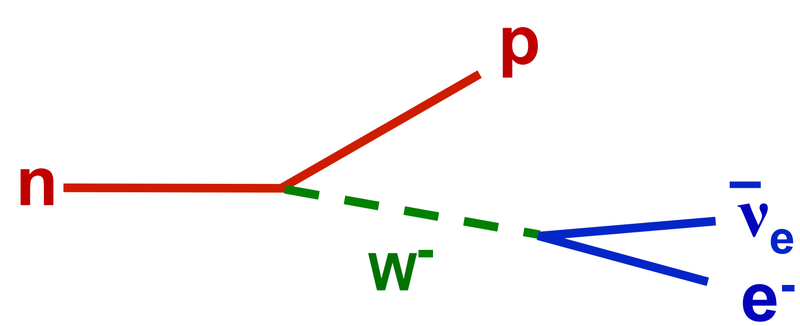
Neutraler Strom



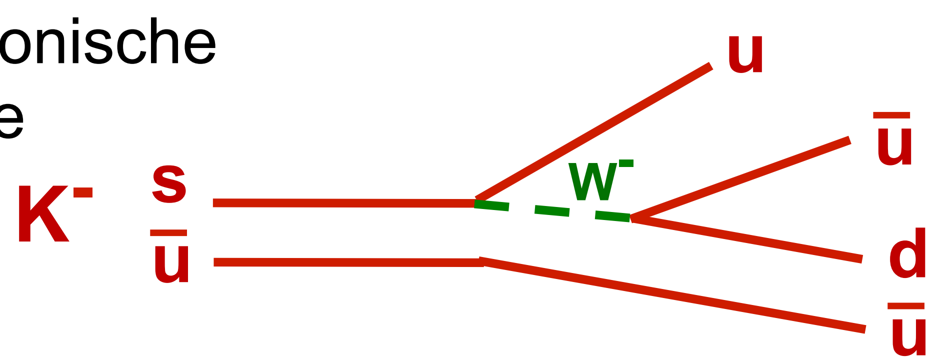
semileptonische
Prozesse

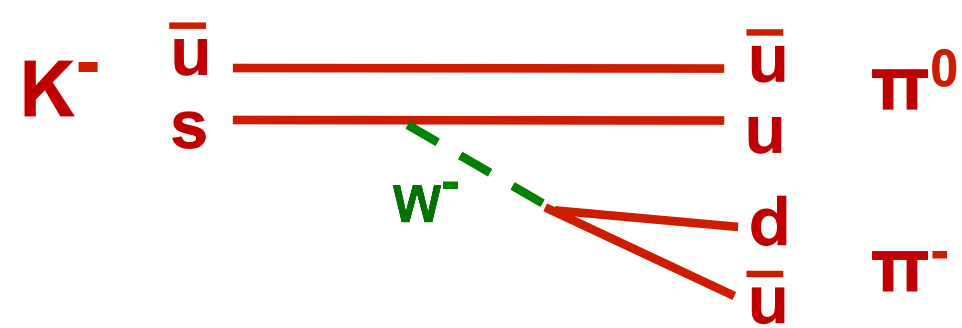




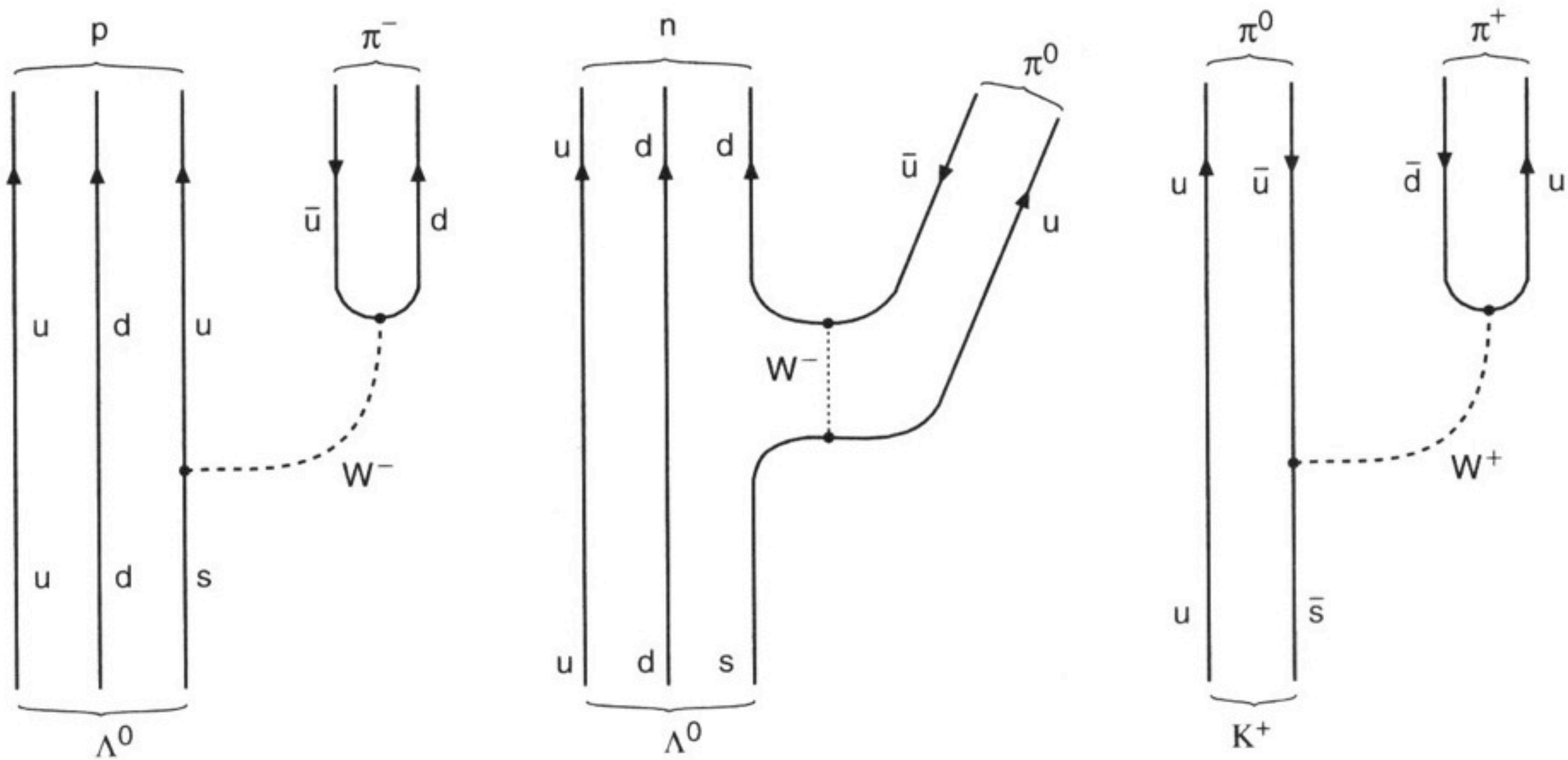


nichtleptonische
Prozesse



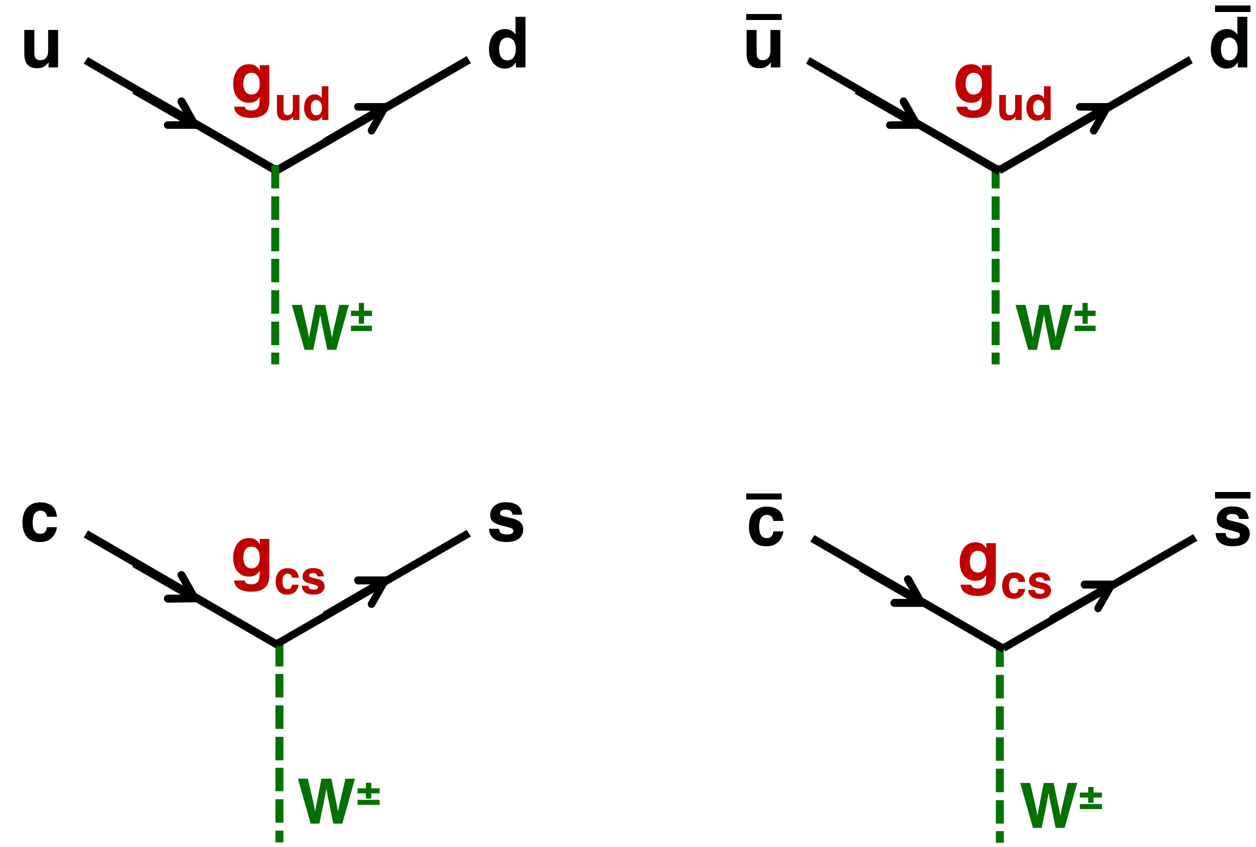


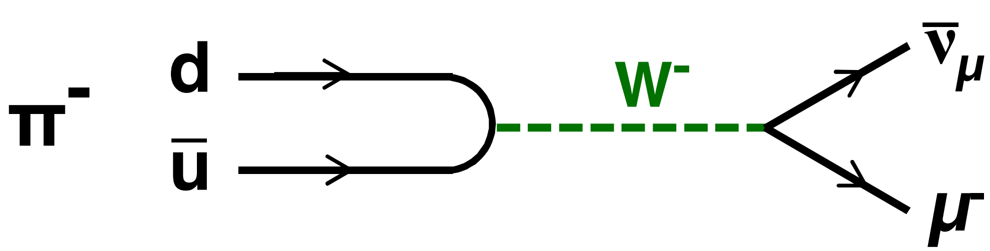
weitere nichtleptonische Prozesse



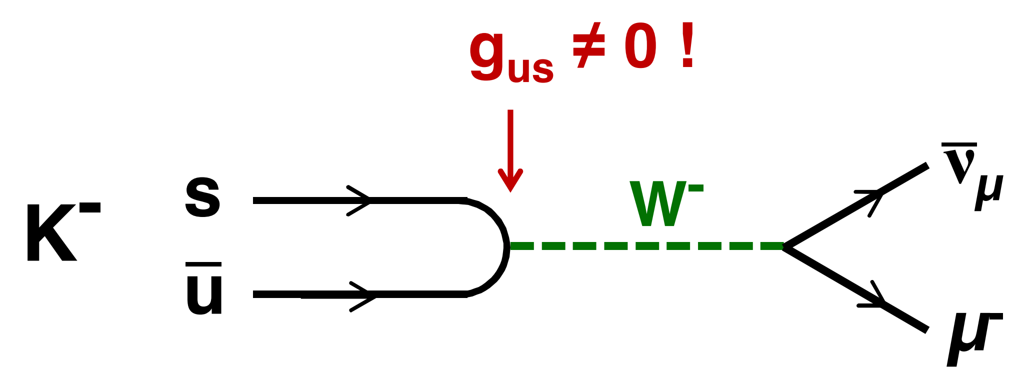
Basisdiagramme

<u>ohne</u>
Quarkmischung



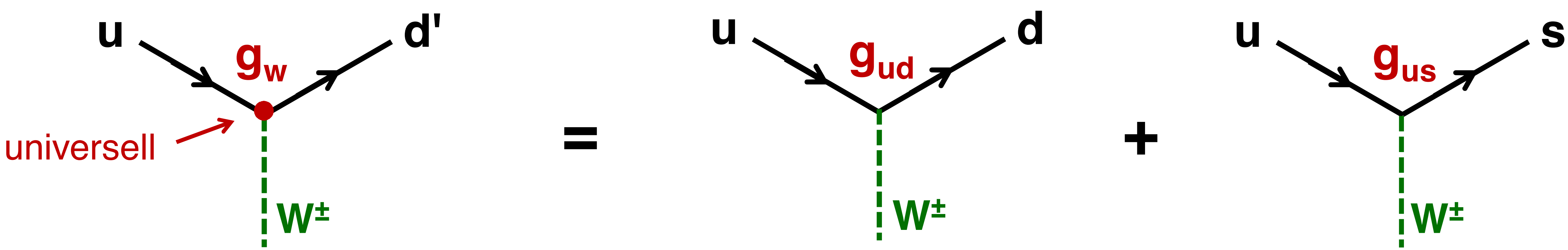


können Pion – Zerfall beschreiben



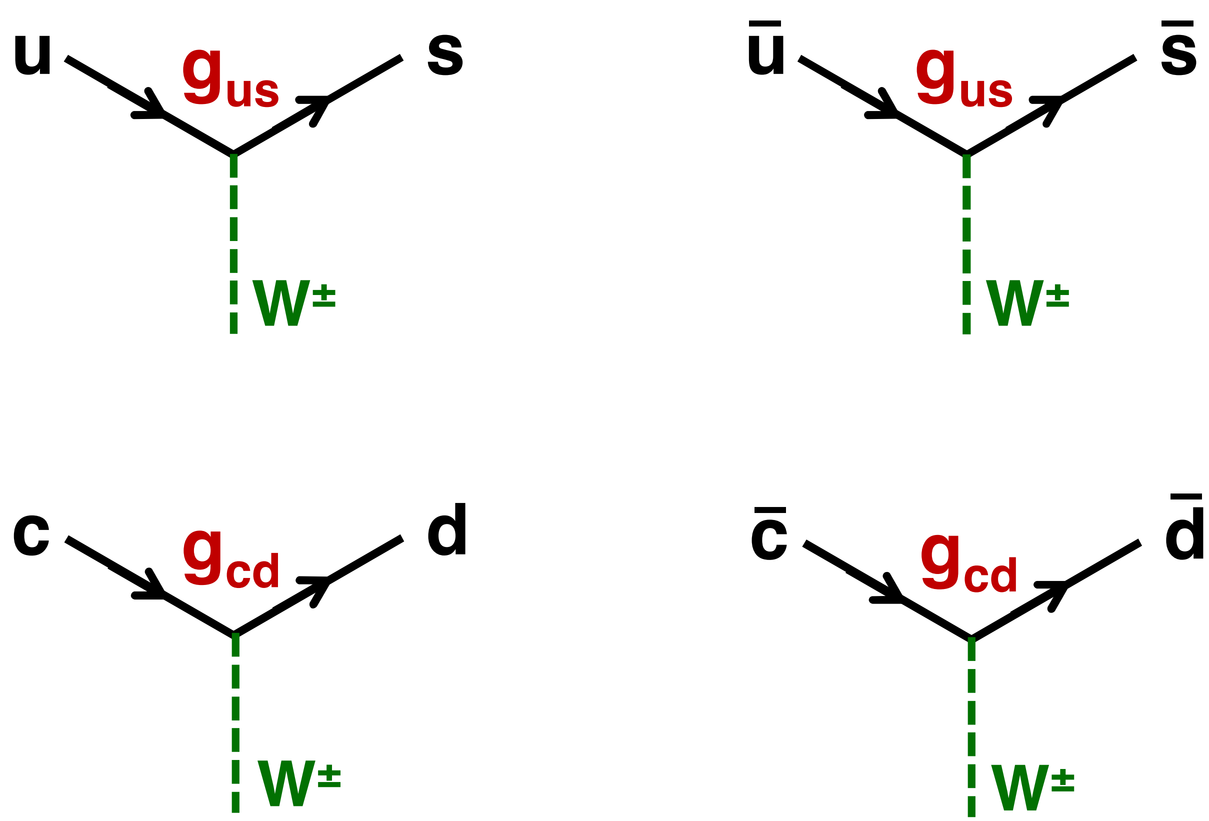
aber Kaon – Zerfall nicht
(beobachtet, lange Lebensdauer)

‘gedrehte Quarkzustände



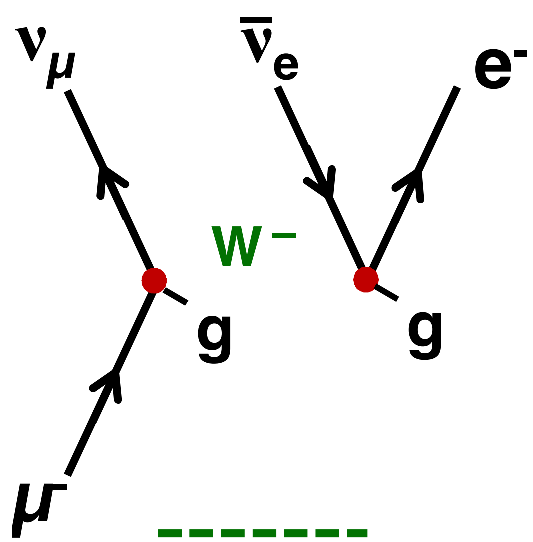
$d' = d \cos\theta_C + s \sin\theta_C$ ⇨ $g_{ud} = g_W \cos\theta_C$ $g_{us} = g_W \sin\theta_C$

Damit sind auch diese Diagramme möglich (aber Kopplung mit $\sin\theta_C$ unterdrückt!)



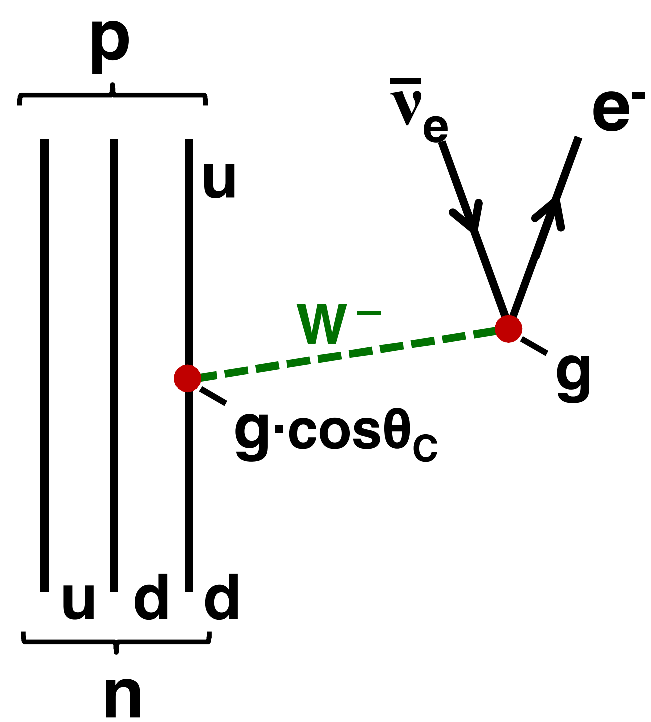
← z.B. Kaon – Zerfall

Bestimmung des Cabibbo-Winkels



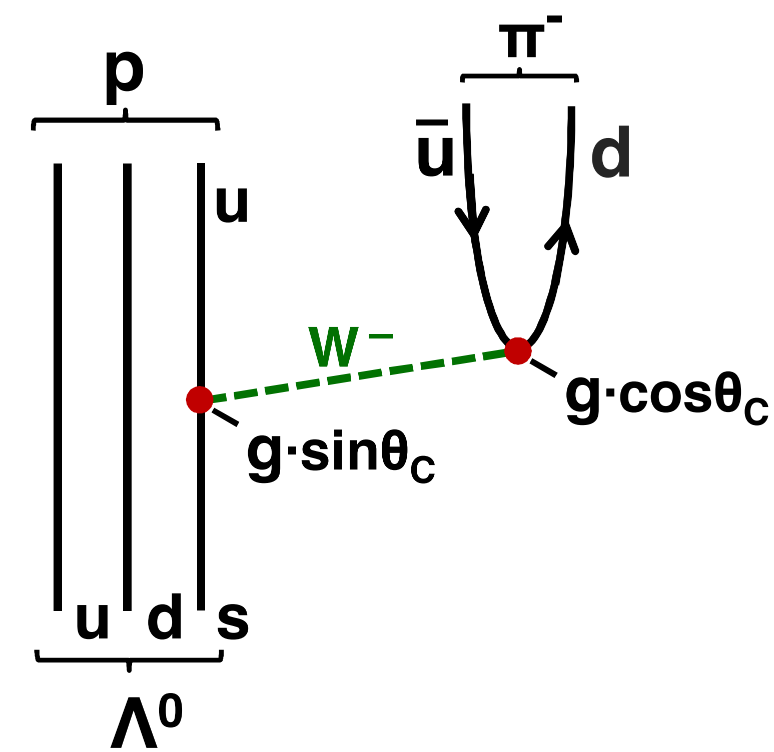
$M_{if} \propto g^2$

leptonisch



$M_{if} \propto g^2 \cdot \cos\theta_C$

semileptonisch
(1 Winkel)



$M_{if} \propto g^2 \cdot \cos\theta_C \cdot \sin\theta_C$

nichtleptonisch
(2 Winkel)

$$\frac{\Gamma(K^- \to \mu^- \bar{\nu})}{\Gamma(\pi^- \to \mu^- \bar{\nu})} \propto \frac{g_{us}^2}{g_{ud}^2} = \tan^2\theta_C \approx \frac{1}{20}$$

Cabibbo-unterdrückt

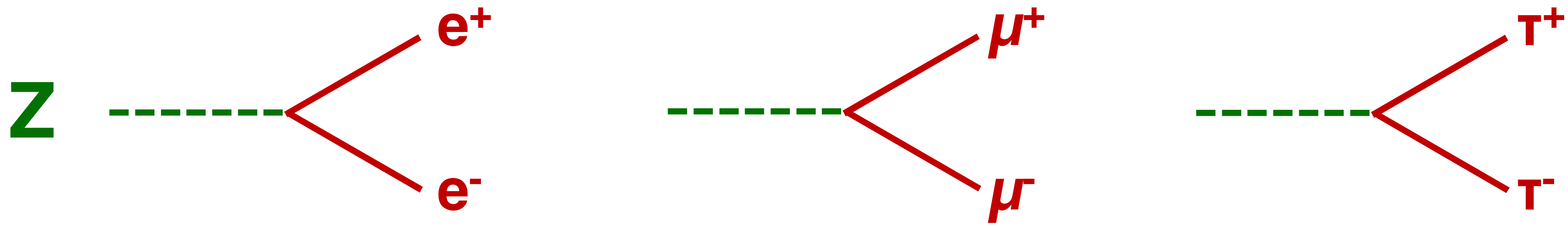
$$\frac{n-\text{Zerfall}}{\mu-\text{Zerfall}} \propto \frac{g_{ud}^2}{g^2} = \cos^2\theta_C$$

$\Longrightarrow$

$\sin\theta_C$	≈ 0.22
$\cos\theta_C$	≈ 0.98
θ_C	$\approx 12.7°$

FCNC sind verboten

diese Zerfälle gibt es



$Z \to \nu_e \bar{\nu}_e$ $\quad Z \to \nu_\mu \bar{\nu}_\mu$ $\quad Z \to \nu_\tau \bar{\nu}_\tau$

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

$Z \to c\bar{c}$ $\quad Z \to b\bar{b}$ $\quad Z \to t\bar{t}$

ABER: diese Zerfälle gibt es **nicht!**

$Z \to e^+\mu^-$ $\quad Z \to e^+\tau^-$ $\quad Z \to u\bar{c}$

$Z \to \nu_e \bar{\nu}_\mu$ $\quad Z \to d\bar{b}$ $\quad Z \to t\bar{u}$

CKM-Matrix

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

CKM-Matrix

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

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

CKM-Matrix in Wolfenstein-Form

It is known experimentally that $s_{13} \ll s_{23} \ll s_{12} \ll 1$, and it is convenient to exhibit this hierarchy using the Wolfenstein parameterization. We define [4–6]

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|,$$

$$s_{13} e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar{\rho} + i\bar{\eta})\sqrt{1 - A^2\lambda^4}}{\sqrt{1-\lambda^2}[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})]}. \tag{11.4}$$

These relations ensure that $\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$ is phase-convention-independent, and the CKM matrix written in terms of λ, A, $\bar{\rho}$, and $\bar{\eta}$ is unitary to all orders in λ. The definitions of $\bar{\rho}, \bar{\eta}$ reproduce all approximate results in the literature. For example, $\bar{\rho} = \rho(1 - \lambda^2/2 + \ldots)$ and we can write V_{CKM} to $\mathcal{O}(\lambda^4)$ either in terms of $\bar{\rho}, \bar{\eta}$ or, traditionally,

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

K. Nakamura *et al.*, JPG **37**, 075021 (2010) (http://pdg.lbl.gov)

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Unitaritätsdreieck

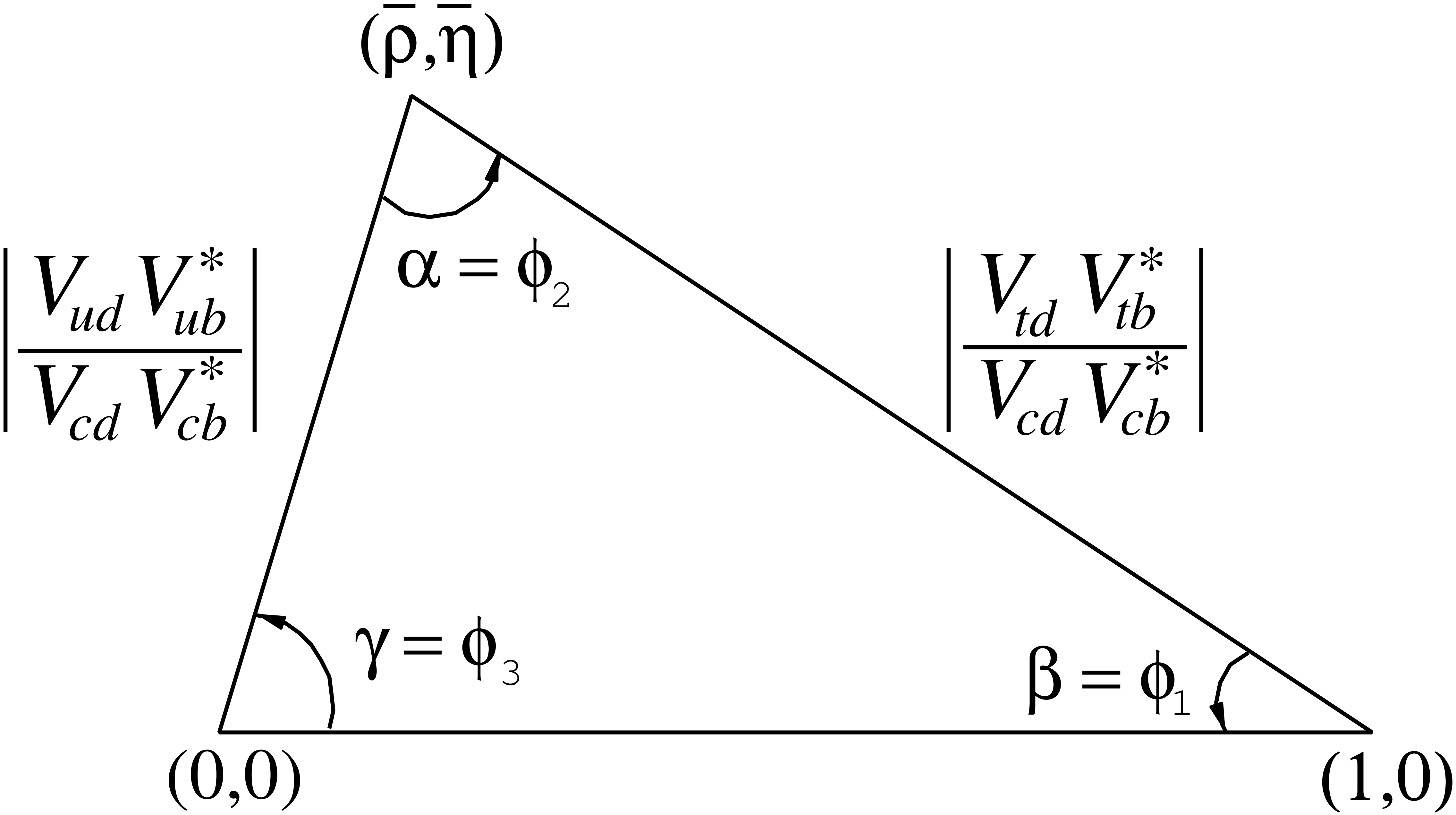

Figure 11.1: Sketch of the unitarity triangle.

The CKM matrix elements are fundamental parameters of the SM, so their precise determination is important. The unitarity of the CKM matrix imposes $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij} V_{kj}^* = \delta_{ik}$. The six vanishing combinations can be represented as triangles in a complex plane, of which the ones obtained by taking scalar products of neighboring rows or columns are nearly degenerate. The areas of all triangles are the same, half of the Jarlskog invariant, J [7], which is a phase-convention-independent measure of CP violation, defined by $\mathrm{Im}\left[V_{ij} V_{kl} V_{il}^* V_{kj}^*\right] = J \sum_{m,n} \varepsilon_{ikm} \varepsilon_{jln}$.

The most commonly used unitarity triangle arises from

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \,, \qquad (11.6)$$

by dividing each side by the best-known one, $V_{cd} V_{cb}^*$ (see Fig. 1). Its vertices are exactly $(0,0)$, $(1,0)$, and, due to the definition in Eq. (11.4), $(\bar{\rho}, \bar{\eta})$. An important goal of flavor physics is to overconstrain the CKM elements, and many measurements can be conveniently displayed and compared in the $\bar{\rho}, \bar{\eta}$ plane.

Processes dominated by loop contributions in the SM are sensitive to new physics, and can be used to extract CKM elements only if the SM is assumed. In Sec. 11.2 and 11.3, we describe such measurements assuming the SM, we give the global fit results for the CKM elements in Sec. 11.4, and discuss implications for new physics in Sec. 11.5.

Unitaritätsdreieck

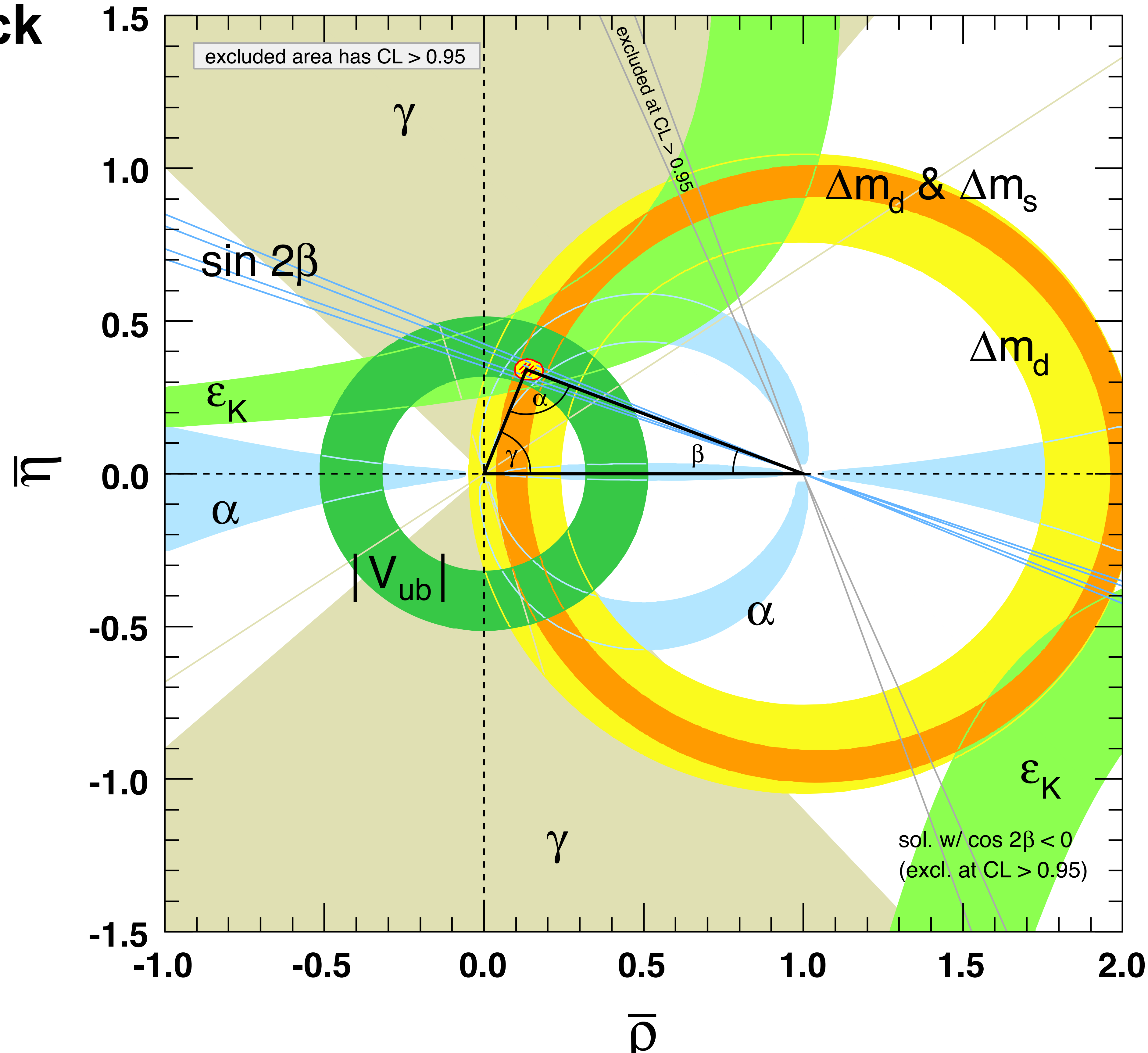

Figure 11.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

CKM-Matrix aktuelle Werte

These values are obtained using the method of Refs. [6,95]. Using the prescription of Refs. [102,118] gives $\lambda = 0.2246 \pm 0.0011$, $A = 0.832 \pm 0.017$, $\bar{\rho} = 0.130 \pm 0.018$, $\bar{\eta} = 0.350 \pm 0.013$ [119]. The fit results for the magnitudes of all nine CKM elements are.

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}, \qquad (11.27)$$

and the Jarlskog invariant is $J = (2.91^{+0.19}_{-0.11}) \times 10^{-5}$.