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SMR.1508 - 1

SUMMER SCHOOL ON PARTICLE PHYSICS

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FLAVOUR PHYSICS

Part 1

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Flavour Physics

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Contents (?)

1. Flavour in gauge theories
2. CKM-matrix, tree level
3. Loop induced decays, CKM cont'nd
4. Effective Hamiltonian, renormalization, operator product expansion precision calculation
5. Hadronic B-decays
6. CP-violation
7. HQET
8. SCET

Mainly B physics (and K)

Very active experimentally!

- B-Factories BaBar and Belle
- Results from Cornell, plans at F.L/CERN

1. Flavours in gauge theories

Gauge - Field - Theory

$\swarrow \qquad \searrow$

Gauge fields	Matter fields
γ, g, W, Z, ...	Quarks, leptons, Higgs..
fixed by symmetry group	largely arbitrary theoretical constr.
$SU(3) \times SU(2) \times U(1)$	

Matter:

- choice of group representation
- how many irreduc. representations
- exper. input : no right-handed W
  only two charges
  $q(2/3, -1/3)$ $\ell(0, -1)$

SU(2) $\begin{cases} \text{Left-handed Quarks and leptons in doublets} \\ \text{right handed Quarks " " " singlets} \end{cases}$

$$Q_i : \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \qquad \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad \updownarrow SU(2)$$

$$L_i : \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_L^\mu \\ \mu_L \end{pmatrix} \qquad \begin{pmatrix} \nu_L^\tau \\ \tau_L \end{pmatrix}$$

$\phi_{\substack{L \\ R}} = \frac{1}{2}(1 \mp \gamma_5)\phi$

$$\begin{array}{llll} u_i: & u_R, d_R & c_R, s_R & t_R, b_R \\ \text{etc} & e_R, \nu_R^e(?) & \mu_R, \nu_R^\mu(?) & \tau_R, \nu_R^\tau(?) \end{array}$$

$$③ \longleftrightarrow ② \longleftrightarrow ① \longleftrightarrow ?$$

Generations, <u>flavors</u> of Quarks and leptons

¿ horizontal Symmetry ? $U(3)$

$$Q_{1,2,3} \qquad L_{1,2,3}$$

Interactions:

- gauge-interactions : $U(3)$ global $\to$ local ?
- Higgs (Yukawa) : $U(3)$ broken

Interactions

$$\mathcal{L} = \underline{\mathcal{L}_{YM}} + \underline{\mathcal{L}_G} + \underline{\mathcal{L}_H} + \underline{\mathcal{L}_Y}$$

$$\mathcal{L}_{YM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$ gauge Fields

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - g[A_\mu, A_\nu]$$

$$\mathcal{L}_G = \sum_i \bar{Q}_i i \not{D} Q_i + \sum_i \bar{L}_i i \not{D} L_i$$

$$\not{D} = \gamma_\mu (\partial^\mu - ig \mathbf{A}^\mu)$$ quarks

$$\mathbf{A}^\mu \hookrightarrow \sum A_j^\mu T_j$$

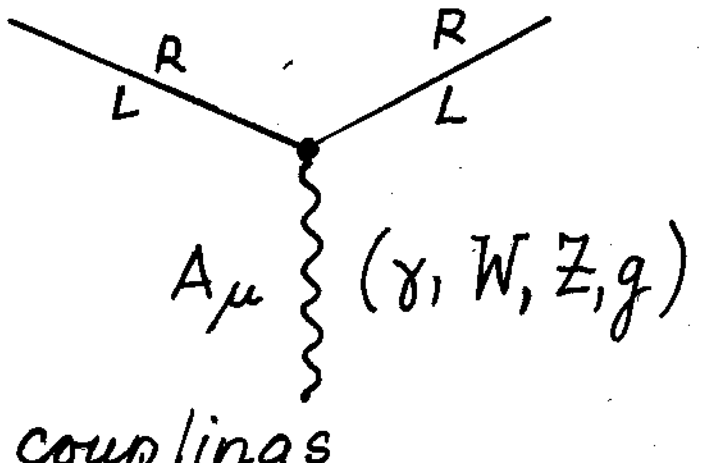
$$\mathcal{L}_H = \partial_\mu H \, \partial^\mu H^* - V(H)$$

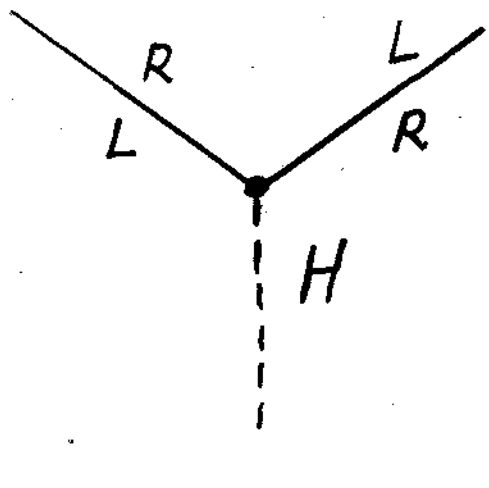
Higgs

representation of Q, L

$$\mathcal{L}_Y = \sum \bar{Q}_{iL} H \Gamma_{ij} U_j + \cdots\cdots$$

- $\mathcal{L}_G$: global $U(3)$ - symmetry (horiz.)





couplings

• Unbroken Symmetry ($\langle H \rangle = 0$)

- gauge symmetries: $SU(3) \times SU(2) \times U(1)$
- Global symmetries: $Q_1 \leftrightarrow Q_2 \leftrightarrow Q_3, \ldots$

$U(3)_L^Q \otimes U(3)_R^u \otimes \ldots$ horizontal symmetry

• broken Symmetry ($\langle H \rangle \neq 0$)

$$\mathcal{L}_y \longrightarrow \mathcal{L}_M = \bar{Q}_i \Gamma_{ij} \langle H \rangle u_j + \ldots$$

$$= \bar{d}_{Li} M^d_{ij} d_{Rj} + \bar{u}_{Li} M^{u\,*}_{ij} u_{Rj} + \ldots$$

M^d, M^u : mass matrices

Eigenvalues: masses of quarks/leptons m_q, m_e

$M \neq 0$: breaks horizontal symmetry (explicitely)

also spontaneous breaking via QCD
→ Goldstone particles (massless)
$\pi, K, \ldots$ (pseudoscalars)

$$m_\pi^2 \simeq \Lambda_{QCD} \cdot m_q$$

* In S.M. can start with M^u diagonal

Basis choice: ('coordinates')

- $Q_i, L_i, u_i, \ldots$ <u>interaction basis</u>

  $\mathcal{L}_G$ diagonal

- $d_{Li}, u_{Li}, d_{Ri}, \ldots$ <u>physical basis</u>

  $\mathcal{L}_M$ diagonal

Transformation (unitary)

$$d_L \to V_d^L d_L$$
$$u_L \to V_u^L u_L \quad \ldots$$

- $V_d^{L+} M^d V_d^R = (m_d, m_s, m_b)$
- $V_u^{L+} M^u V_u^R = (m_u, m_c, m_t)$

write $\mathcal{L}_G$ in physical basis

$$\mathcal{L}_G = \bar{u}_{Li} \left(V_u^{L+} V_d^L \right)_{ij} d_{Lj} \frac{g}{\sqrt{2}} W + h.c.$$

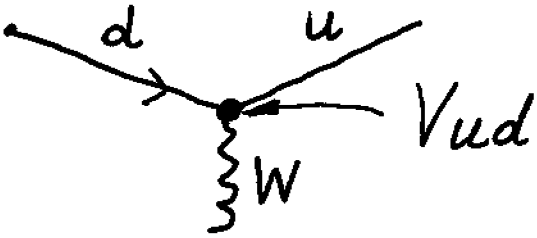
$$+ \bar{u}_{Li} \underbrace{\left(V_u^{L+} V_u^L \right)_{ij}}_{\delta_{ij}\,!} u_{Lj} \, (Z, \gamma, g)$$

neutral current flavour diagonal: GIM 1970 from gauge universality + repetition

Set $V = U_{CKM} \equiv \left(V_u^{L+} V_d^{L} \right)$

Cabibbo - Kobayashi - Maskawa

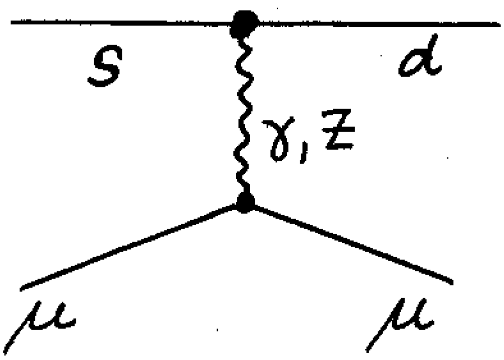
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad VV^+ = 1$$



measured in various decays (later)

Neutral current: γ, Z

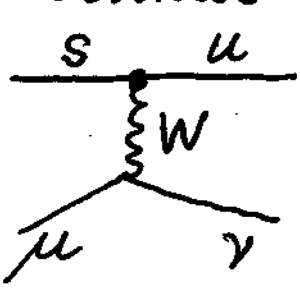
GIM mechanism insure no flavour transitions at tree level and suppression in loops



$\rightarrow \quad K^0(\bar{s}d) \rightarrow \mu^+\mu^-$

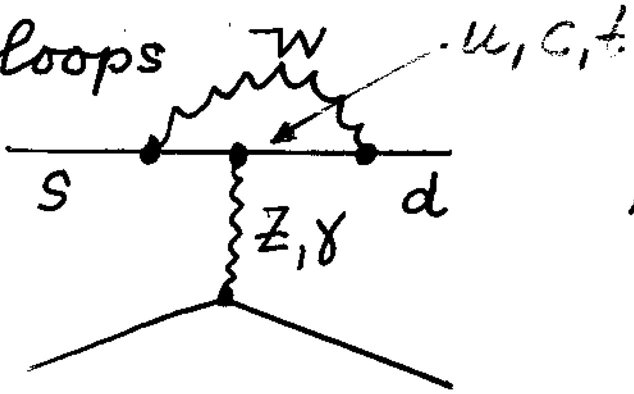
absent

contrast



$K^+(\bar{s}u) \rightarrow \mu\nu$

loops



$$A_{tot} = c\sum_i A_i \qquad i = u, c, t$$

$$= V_{us}V_{ud}^* \cdot f\left(\frac{m_u}{M_W}\right) + V_{cs}V_{cd}^* \, f\left(\frac{m_c}{M_W}\right) + V_{ts}V_{td}^* \, f\left(\frac{m_t}{M_W}\right)$$

$$\sum = 0$$

$$V_{ts}^* V_{td} \simeq 0$$

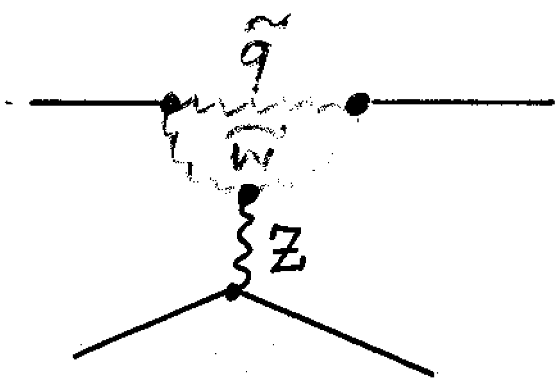
$$A_{tot} \approx \left(V_{us}V_{ud}^* - V_{cs}V_{cd}^*\right)\left(f\left(\frac{m_u}{m_W}\right) - f\left(\frac{M_c}{M_W}\right)\right)$$

<u>GIM-suppression</u>

(hard, soft)

- $\dfrac{m_u^2 - m_c^2}{M_W^2} \ll 1$
- $\log\left(\dfrac{m_u^2}{m_c^2}\right)$

→ FCNC : small in standard model
standard test for new physics



limits on SUSY

$K \to \mu\mu$, $b \to s\gamma$, $b \to d\gamma$ $\qquad \Delta F = 1$

$m_K - m_{\bar{K}}$, $m_B - m_{\bar{B}}$ $\qquad \Delta F = 2$

- Symmetries: crucial ingredient (estetics, technical, physical)
  Lorentz, gauge, P, C, T, CP, GR, ...
- Physics invariant under transformation"

Operator $\phi(x)$ $\quad x = \vec{x}, t$

Transformation rule needed

$$\phi(\vec{x},t) \longrightarrow R_\phi\, \phi(\vec{x}\,', t') \qquad \begin{array}{l} \vec{x} \to \vec{x}\,' \\ t \to t' \end{array}$$

Parity: $P: \vec{x} \to -\vec{x}\,,\ t \to t$

Time reversal: $T: \vec{x} \to \vec{x}\,,\ t \to -t$

① $P:\ \psi(\vec{x},t) \to \gamma_0\, \psi(-\vec{x},t)$

$$\phi_{S,P}\ (\vec{x},t) \to \phi_S\,(-\phi_P)\,(-\vec{x},t) \ \ldots$$

$$\underbrace{(1-\gamma_5)\,\psi(\vec{x},t)}_{L\,(eft)} \to \gamma_0 (1-\gamma_5)\ldots = \underbrace{(1+\gamma_5)\,\gamma_0\,\psi(-\vec{x},t)}_{R\,(ight)}$$

② C: Charg. conjugation: particle $\leftrightarrow$ Antiparticle

$\psi \to C\,\bar{\psi}^T \qquad C = i\gamma_0\gamma_2$ (Dirac-R)

$V^\mu \to -V^{\mu +} \qquad \bar{\psi}_1 \gamma_\mu \psi_2 \to -\bar{\psi}_2 \gamma_\mu \psi_1$

$$\bar{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \to +\bar{\psi}_2 \gamma_\mu \gamma_5 \psi_1$$

③ CP: Combined C, P

$$\bar{\psi}_1 \gamma_\mu\,(\gamma_\mu\gamma_5)\,\psi_2 \longrightarrow \bar{\psi}_2 \gamma_\mu\,(\gamma_\mu\gamma_5)\,\psi_1$$

All connected by CPT-Theorem: "Proper"* field theory invariant under CPT

* Local. Lorentz-invariant

$$\mathcal{L}^g \cong W_\mu^- \bar{d}_{L_j} \gamma^\mu u_{L_i} V_{ji}^+ + W_\mu^+ \bar{u}_i \gamma^\mu d_j V_{ij}$$

$$\downarrow CP$$

$$\mathcal{L}^g_{CP} \cong W_\mu^+ \bar{u}_{L_i} \gamma^\mu d_{L_j} V_{ji}^+ + W_\mu^- \bar{d}_j \gamma^\mu \bar{u}_i V_{ij}$$

$$\mathcal{L}^g_{CP} = \mathcal{L}^g : V_{ij} = V_{ji}^+ = V_{ij}^*$$

- $\boxed{\text{Complex coupling: CP-violation}}$

Phases necessary; not always sufficient
(Q.M.: Some phases irrelevant)

all s.m. CP. violation in V_{CKM}

$N \times N$ unitary matrix N^2 Parameters

$$N^2 = \underbrace{\frac{1}{2} N(N-1)}_{\text{angles}} + \underbrace{\frac{1}{2} N(N+1)}_{\text{phases}}$$

$2N-1$ phases can be removed

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

only phases for $N \geq 3$: K.M.

- flavor $\longleftrightarrow$ CP violation
- need 3 "generation" to have effect (Loops!)

Issues in flavour physics

① Determine parameters in S.M.

a) Masses of quarks + leptons

$m_{\nu_e} \sim 10^{-2}$ eV $\quad m_{\nu_\mu} \sim 10^{-2}$ eV $\quad m_{\nu_\tau} \sim 10^{-1}$ eV

$m_e \cong 0.5$ MeV $\quad m_\mu \cong 102$ MeV $\quad m_\tau \cong 1800$ MeV

$m_\mu \cong 5$ MeV $\quad m_c \simeq 1200$ MeV $\quad m_t \cong 175$ GeV

$m_d \cong 7$ MeV $\quad m_s \cong 100$ MeV $\quad m_b \cong 4200$ MeV

- m_ν : Oscillations, cosmology, $\beta\beta$
- m_e, m_μ, m_τ : kinematical (also m_t)
- m_u, m_d : chiral perturbation theory
  χPT

$m_u, m_d \ll m_\pi$!

Deviation from $m_u = 0 = m_d$ prediction
(see p. 5)

- $m_u, m_d = 0$: $\pi\pi$-scattering $\sim s$
  $m_\pi^2 = 0$

- $m_u, m_d \neq 0$: $m_\pi \simeq \chi \cdot (m_u + m_d)$ etc.

- m_s : from χPT, K, $\phi (= \bar{s}s)$, Lattice
  Sum rules
  scale dependence $m_s(2\,GeV)$

- m_c : various methods $m_c(1\,GeV)$

- m_t : various methods, heavy quarks,..

masses not directly observable.

b) V_{CKM} - elements V_{ub}...

$$\text{rough: } V_{CKM} \simeq \begin{pmatrix} 1 & \lambda & \frac{1}{2}\lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix} \quad \lambda \simeq 0.2$$

many methods

2. Check flavour structure

flavour changing neutral currents (loops) in rare decays + ν-oscill

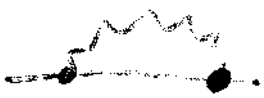
3. Check CP-violation.

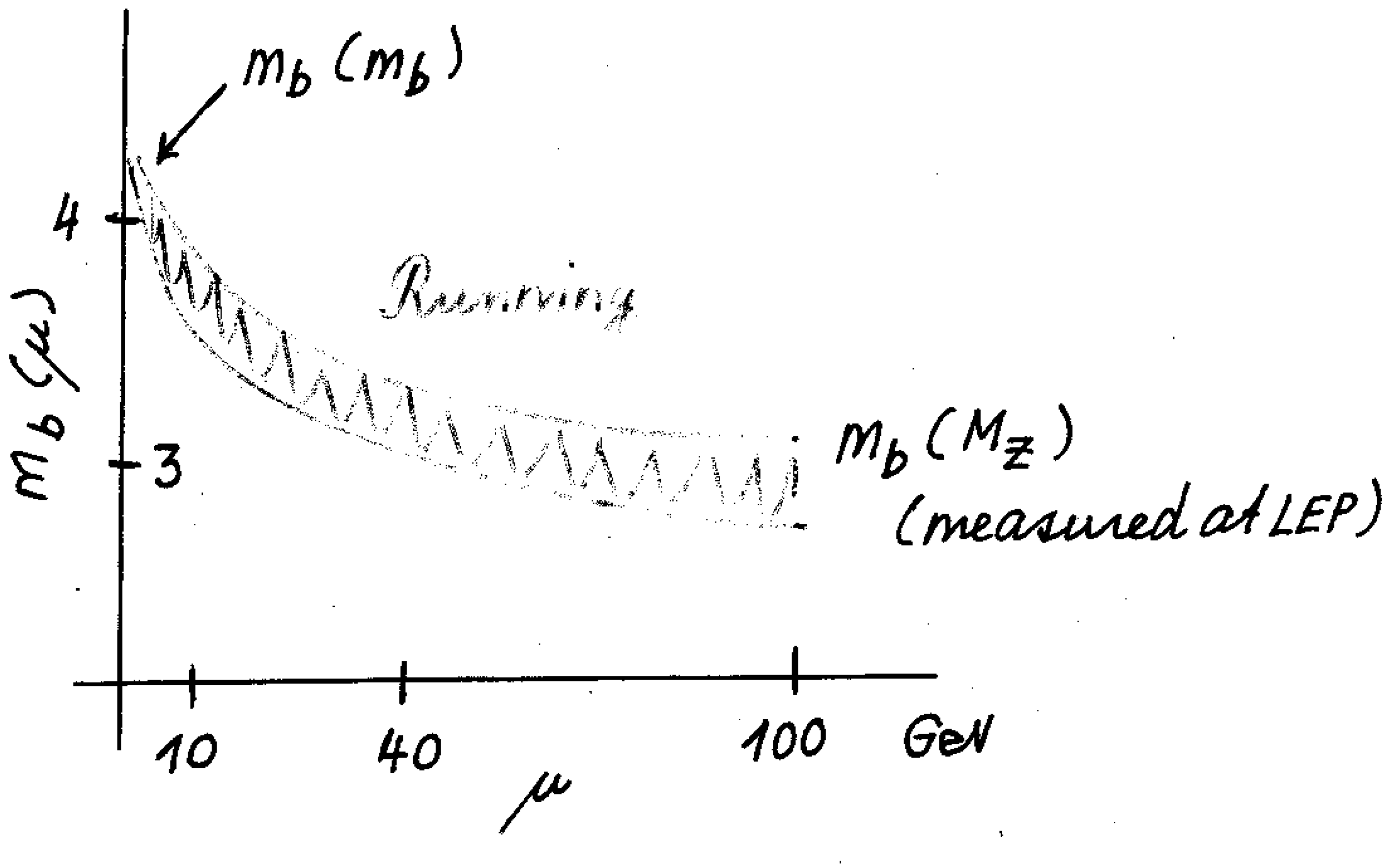
* ALL is technical work (QCD related)

Comment: masses are scale dependent (as any parameter in $\mathcal{L}$)

$$\frac{d \log m(\mu)}{d \log \mu} = b \cdot g^2(\mu) + \dots$$

$$b = -\frac{3}{8\pi^2} C_2 \leftarrow (n^2-1)/n$$

 $+ \dots$



extremely important for G.U.T.

(4) Explain why:
3 generations
hierarchical pattern of parameters
Vague Ideas:
horizontal gauge symmetries
geometrical studies in higher
dimensions (strings)
grand unification (SU(5))

example: table (p. 11) indicates
lepton-quark relation

$\leftrightarrow$ irreducible representation!
16 fields $(e, \nu, d(3)\ u(3)) \Rightarrow$
SO(10) group as gauge
group (or SU(5))
quarks leptons "undistinguishable"
proton decay $p \to \pi e$
$(p \to \pi\pi$ no!$)$

* Speculative, imagination, mathem.

Example: d, s quarks

- $\frac{m_d}{m_s} \simeq \frac{1}{20}$ $\theta_C \simeq \frac{1}{5} \sim \frac{1}{\sqrt{20}}$

$$V_{CKM} \simeq \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

$$V_{CKM}^{+} M^{d} V_{CKM} = \begin{pmatrix} m_d & 0 \\ 0 & m_s \end{pmatrix}$$

$$\Rightarrow \quad M^{d} \simeq \begin{matrix} 0 & \epsilon \\ \epsilon & 1 \end{matrix} \qquad \theta_C \simeq \epsilon \quad \frac{m_d}{m_s} \simeq \epsilon^2$$

"texture-zero"

- three generations

$$\begin{pmatrix} 0 & \epsilon^3 & 0 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ 0 & \epsilon^2 & 1 \end{pmatrix}$$

Eigenvalues: $\epsilon^4 : \epsilon^2 : 1$

$\theta_{23} \simeq \epsilon^2$; $\theta_{12} \simeq \epsilon$

θ_{13} small

d, s, b : $\epsilon \simeq 0.15$
u, c, t : $\epsilon \simeq 0.08$

caused by symmetries ?
geometry ?

2. The CKM-Matrix

(p.7) V unitary $\rightarrow$ parametrization with 3 angles, 1 phase

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

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

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

δ indicates CP-violation
can be eliminated (unphysical) if:

- any 2 quarks of same charge have same mass
- any of the $s_{ij} = 0$

example: $s_{12} = 0$ $c_{12} = 0$

$$V = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ s_{23}s_{13}e^{i\delta} & c_{23} & s_{23} \\ c_{23}s_{13}e^{i\delta} & -s_{23} & c_{23} \end{pmatrix}$$

$u_L \to e^{-i\delta}u_L \Rightarrow V_{11}, V_{21}, V_{31} \sim e^{i\delta}$, V_{13} real
$d_L \to e^{i\delta}d_L \Rightarrow$ all real

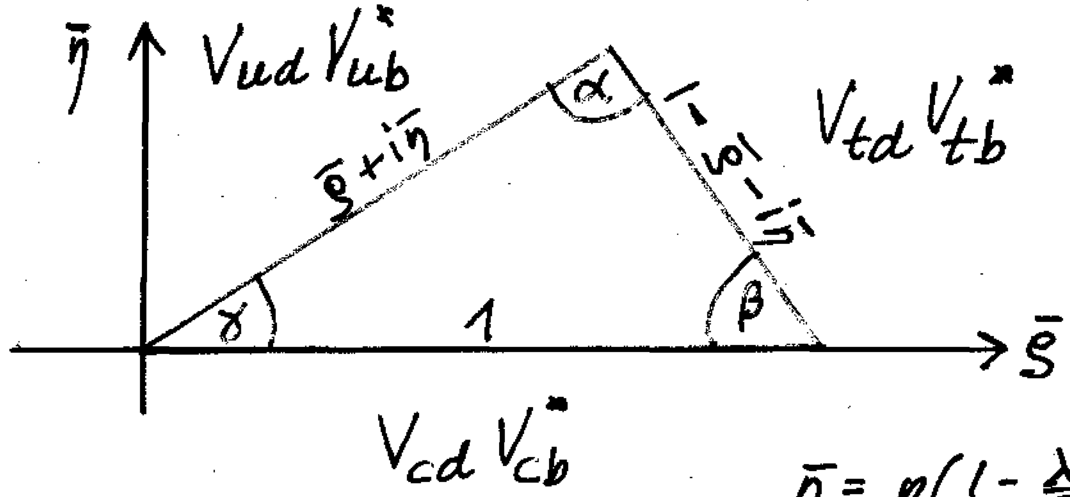
- CP-viol: $(m_u^2 - m_c^2)(\dots)\, s_{12}s_{13}s_{23} \cdot \sin\delta$ Jarlskog

More useful parametrization (Wolfenstein)

$$V \cong \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity: triangle relations

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

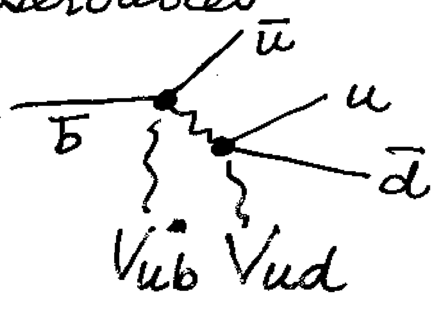


$$\bar\eta = \eta\left(1-\frac{\lambda^2}{2}\right)$$
$$\bar\rho = \rho\left(1-\frac{\lambda^2}{2}\right)$$

more precise

Related to observables

exp: $B \to \pi\pi \sim$



Precise tests of S.M. and 3 generations

Major effort to "check" triangle"

measure lengths: Rates, non-CP
measure angles: CP-violation
(area of $\Delta \simeq$ CP-violation)

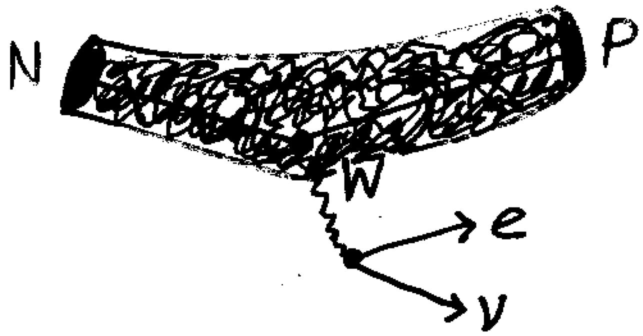
Relationship between V_{ij} and (experimental) observables difficult
complicated (and interesting!) theory!

Goal: Verify / contradict tringle

must include possible new physics in analysis
possibilities:
4 generation: triangle $\rightarrow$ qudriangle
new $\Delta F = 1,2$: interpret lengths differently

Calculation: Tree level processes
loop induced ($\sim V_{td}$)

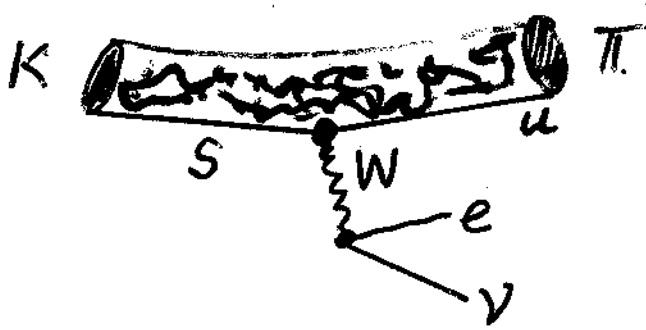
Tree-level-processes



superallowed β transition

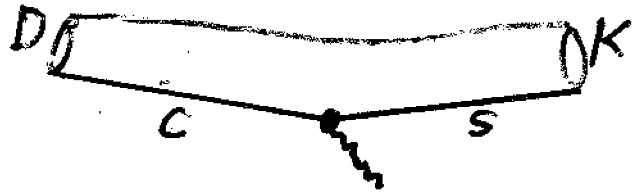
$|V_{ud}| = 0.9736 \pm 0.0005$

many corrections

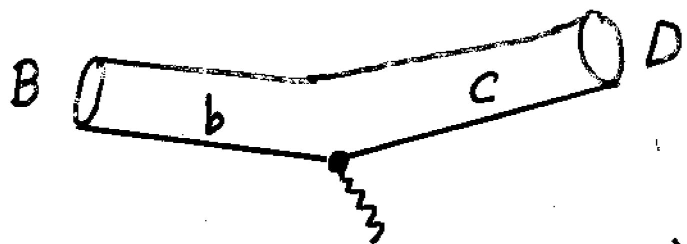


$|V_{us}| = 0.2240 \pm 0.0036$

chiral perturbation theory

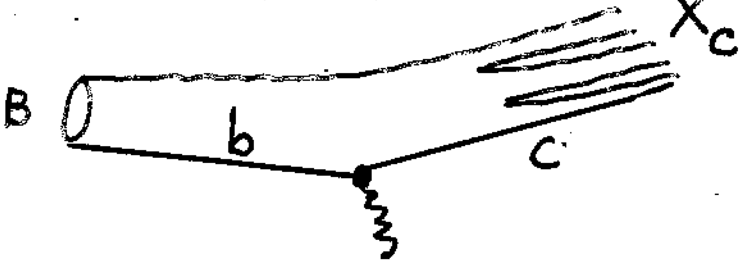


$|V_{cs}| = 1.01 \pm 0.04$



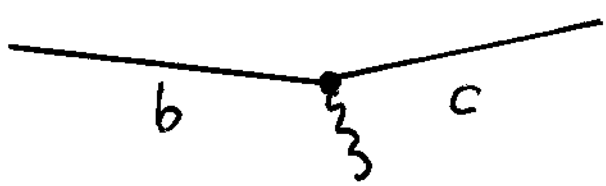
exclusive:

$|V_{bc}| = (42.1 \pm 1.9)10^{-3}$



inclusive:

$|V_{bc}| = (41.4 \pm 1.3)10^{-3}$



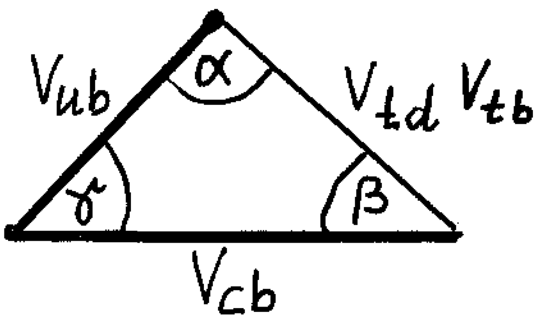
exclusive:

$|V_{ub}| = (3.30 \pm 0.7)\,10^{-3}$

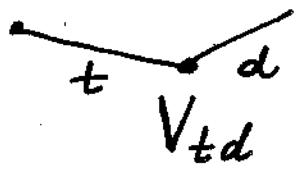
inclusive:

$|V_{ub}| = (4.09 \pm 0.8)\,10^{-3}$

3. Loop induced decays



V_{ub}, V_{cb} from tree (little new physics)



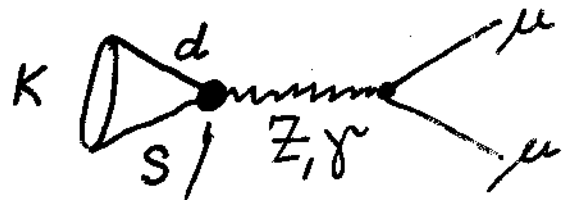
- need t-decays → NO
- loops with t

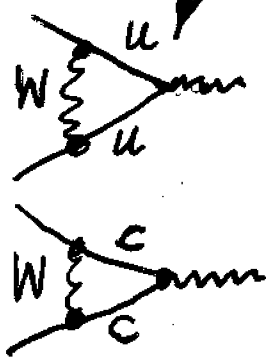
similarly V_{ts}

- angles β, α, γ need loops to

Flavour loops!

① K-physics





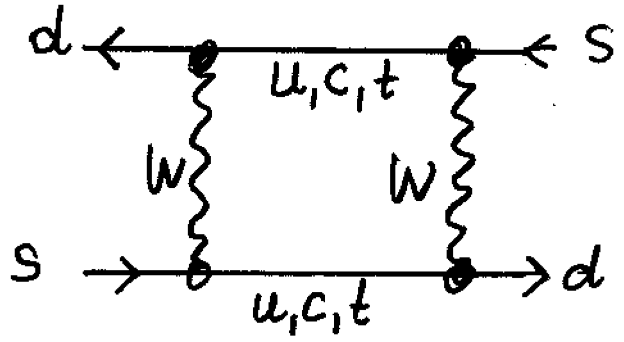
$$\left.\begin{array}{l} V_{ud}V_{us}^{*}\, f(m_u) \\ V_{cd}V_{cs}^{*}\, f(m_c) \end{array}\right\} \lambda G_F \left(\frac{m_u^2 - m_c^2}{M_W^2}\right)$$

$G \simeq \frac{g^2}{M_W^2} \sim 10^{-5}\,\mathrm{GeV}^{-2}$

divergent

finite, small

similar: Δm_K : $K^0 - \bar{K}^0$ mixing



box-diagram

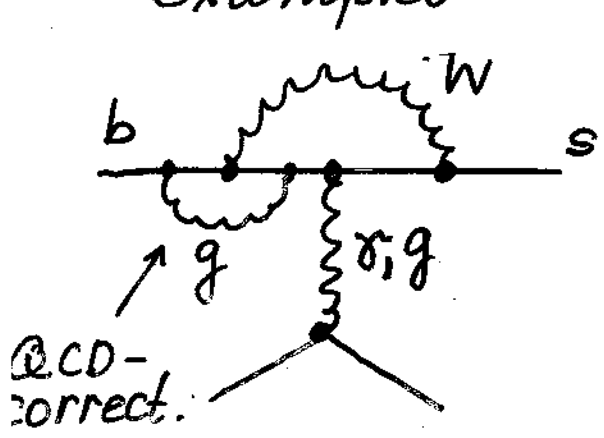
also cancellations

$\Rightarrow$ Effects prop. $(m_u^2 - m_c^2)/M_W^2$

pre 1974 : no charm quark: no or incurate predictions $\rightarrow$
Charm quark foreseen by GIM (1970) and estimate of mass (~ 1.5 GeV)!

- $(m_u^2 - m_c^2)/M_W^2$: linear GIM-cancellation
- In more complicated graphs also $\log\left(\frac{m_u^2}{m_c^2}\right)$: logarith. GIM much less suppressed!

examples:



penguin-diagram

$b \rightarrow s\gamma$

$c \rightarrow u\gamma$ (s, b, d)

GIM-softening: higher order corrections important!

$c \to u\gamma$: $BR \sim 10^{-18}$ L.O.

$BR \sim 10^{-12}$ L.L.

$BR \sim 10^{-7}$ NLL

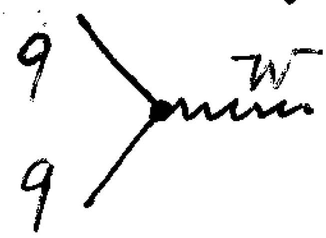
LL: $G_F (m_s^2 - m_W^2)/M_W^2 \sim G_F \cdot 10^{-6}$

NLL: $G_F \, \alpha_s \log\left(\frac{m_s^2}{m_d^2}\right) \sim G_F \, 10^{-1} \ldots\ldots$

Aside: Effective Hamiltonian
(no QCD)

standard example: Fermi - theory

$$\mathcal{L}[W,q] \simeq W^{\mu} W^{\nu} (k^2 - M_W^2) g_{\mu\nu} + \cdots$$
$$+ g J_{\mu} W^{\mu} + h.c. + \cdots$$



$$J_{\mu} = \bar{q} \gamma_{\mu} (1 - \gamma_5) q$$
$$q = u, d, s, \ldots$$
$$m_q \ll M_W$$

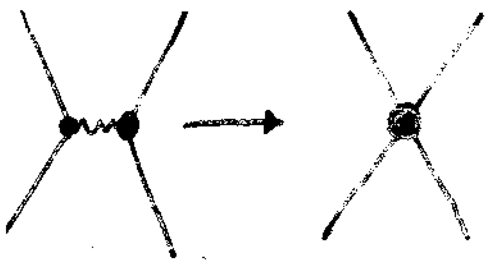
- at $E(q) \ll M_W$ W not produced
  W only "internal"

"Integrate" out W

① EoM: $2W^{\mu}(k^2 - M_W^2) + g J^{\mu} = 0$

$$W^{\mu} = -gJ^{\mu} / 2(k^2 - M_W^2)$$

$$\mathcal{H}_{eff}[q] = -\frac{g^2}{4} J_{\mu} J^{\mu} \frac{1}{k^2 - M_W^2}$$



$$= \underbrace{\frac{g^2}{4M_W^2} \sum_n \left(\frac{1}{M_W^2}\right)^n}_{C_n} \underbrace{\left(k^{2n} J_{\mu} J^{\mu}\right)}_{O_n[q]}$$

② Path integral:

$$\sim \int [dW]\, e^{i\int dx\, \mathcal{L}[W,q]}$$

$$\to \quad S_{eff} \cong \int dx\,dy\, g^2 J_\mu(x)\, \Delta^\mu_\nu\, J^\nu(y)$$

$$\Delta^\mu_\nu = \int \frac{d^4k}{(2\pi)^4}\, e^{-ik(x-y)} \frac{g^\mu_\nu}{k^2 - M_W^2}$$

$$k^2 \ll M_W^2 \to \quad \Delta^\mu_\nu \sim \delta(x-y)$$

same result

need to consider $J_\mu(x) J^\nu(y)$
$x \to y$

Operator product expansion

③ general

$$\mathcal{L}[a, b, .. ; A, B, C..] \quad m_{a..} \ll m_{A...}$$

effective theory for $a, b..$

$$\mathcal{H}_{eff}\, (\mathcal{L}_{eff}) = \sum_n C_n(A,..)\, O_n[a,..]$$

effective Hamiltonian

of interest: $\langle \mathcal{H}_{eff} \rangle$ matrixelements

$$\langle \mathcal{H}_{eff} \rangle = \sum C_n \langle O_n \rangle$$