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Flavour structure of weak charged currents

Status of the CKM Quark Mixing Matrix

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based on Review with Gilman & Renk (RPP)

1 Weak coupling of quarks

2 Parametrization of Mixing Matrix

3 Experimental Constraints on CKM Matrix Elements by tree-level processes:
$V_{ud}, V_{us}, V_{cs}, V_{cb}, V_{ub}$
Fit for mixing angles 3 Gen., ≥ 4 Generations

4 Exp. Constraints by loop-level process
CP violation in K system: ε, ε'
B^0 Mixing ΔM_{B_d} ΔM_{B_s}
CP violation in B-System: $\sin 2\beta$

5. General fit including CP phase δ_{13}

6. Summary

Mixing Matrix

Standard Parametrization, P.O.E.

Chau & Keung, Harari & Leurer, Fritzsch & Plankl, ...

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

$$
\begin{matrix} d & \quad s & \quad b \end{matrix}
$$

P.O.E. <u>Approximate form</u>

neglecting terms with $s_{13}^2 \ll s_{23}^2 \ll 1$

$$\left\{ \begin{matrix} c_{12} & s_{12} & s_{13} e^{-i\delta} \\ -s_{12} & c_{12} & s_{23} \\ s_{12} s_{23} - s_{13} c_{12} e^{i\delta} & -s_{23} & 1 \end{matrix} \right]$$

Approximate Form, notation of Wolfenstein

$$\begin{Bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{Bmatrix}$$

not suitable for describing CP violation in K decays

Summary

1. Mixing matrix well determined by present data on weak decays of b, c, s - quarks, except $b \to u$
2. Weak mixing angles show hierarchy $\sin\theta_{12} > \sin\theta_{23} > \sin\theta_{13}$
3. Coupling to fourth generation limited $\sin\theta_{14} < 0.10$
4. Constraints from lengths of the sides (from $|V_{ub}|$, $|V_{cb}|$ and $|V_{td}|$) and independently from CP violating processes (ε_K and $\sin 2\beta$) indicate the same region for the apex of triangle

   $\mathrm{Re}\, V_{td} = 0.0071 \pm 0.0008$

   $\mathrm{Im}\, V_{td} = -0.0032 \pm 0.0004$

   $\bar{\xi} = 0.22 \pm 0.10$, $\bar{\eta} - 0.35 \pm 0.05$

   VALUE OF CP PHASE $\delta_{13} = 59° \pm 13°$

   $J = (3.0 \pm 0.3)\, 10^{-5}$
5. CP violation in quark sector "explained" but not sufficient for baryon asymmetry

Experimental input from tree-level processes

V_{ud} : beta decays of mirror nuclei $0^+ \to 0^+$

neutron decay of polarized neutrons

$$\boxed{V_{ud}} = 0.9734 \pm 0.0008$$

V_{us} : from K_{e3} (vector) decays

$$\boxed{V_{us}} = 0.2196 \pm 0.0026$$

V_{cd} : from charm production by neutrinos and antineutrinos

$$\boxed{V_{cd}} = 0.224 \pm 0.016$$

V_{cs} : from hadronic decays of W bosons at LEP, compared to leptonic W decays

$$\boxed{V_{cs}} = 0.996 \pm 0.013$$

V_{cb} : average of inclusive and exclusive leptonic B decays

$$\boxed{V_{cb}} = (41.2 \pm 2.0)\, 10^{-3}$$

V_{ub} : inclusive and exclusive charmless B decays

$$\boxed{V_{ub}} = (3.6 \pm 0.7)\, 10^{-3}$$

Elements of Quark Mixing Matrix 2002, may, Vietri & PDG review

from experimental constraints and unitarity, 3 Generations

	d	s	b
u	0.9741 – 0.9756	0.219 – 0.226	0.0025 – 0.0048
c	-0.219 – 0.226	0.9732 – 0.9748	0.038 – 0.044
t	0.004 – 0.014	-0.037 – 0.044	0.9990 – 0.9993

Allowed ranges of mixing angles and phase δ_{13}

3 Generations

Minimum χ^2 by scanning parameter space of 3 angles and one phase

$$\sin \theta_{12} = 0.2229 \pm 0.0022$$
$$\sin \theta_{23} = 0.0412 \pm 0.0020$$
$$\sin \theta_{13} = 0.0036 \pm 0.0007$$

For phase δ_{13}, use loop-level processes in addition

- B^0 Mixing : ΔM_{B_d} measurement, ΔM_{B_s} limit
- ε_K, ε': CP violating process in K system
- $\sin 2\beta$: CP violating process in B system

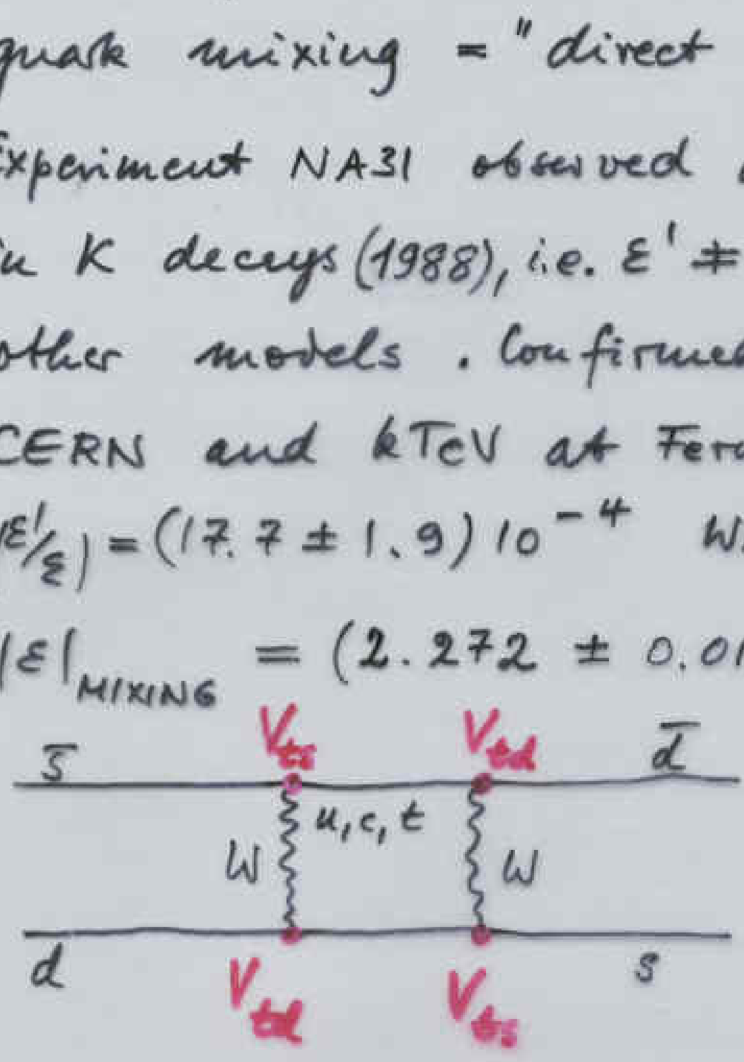
CP Violation in K System

Discovery 1964, triggered Kobayashi-Maskawa Model of CP violation through weak quark mixing = "direct CP Violation"

Experiment NA31 observed direct CP Violation in K decays (1988), i.e. $\varepsilon' \neq 0$, excluding other models. Confirmed by NA48 at CERN and kTeV at Fermilab 1999.

$Re(\varepsilon'/\varepsilon) = (17.7 \pm 1.9)\, 10^{-4}$ WA 2001

$|\varepsilon|_{MIXING} = (2.272 \pm 0.017)\, 10^{-3}$



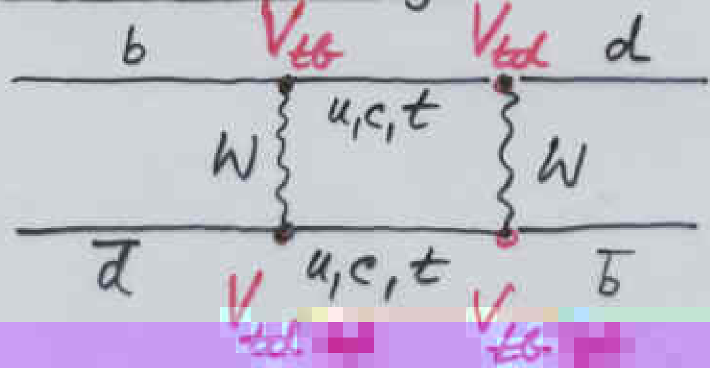
Leading term $|\varepsilon_K| \sim B_K \{ |V_{ts}^* V_{td}|^2 \eta_{tt} S(x_t, x_t)$
$+ 2 |V_{ts}^* V_{td} V_{cs}^* V_{cd}| \eta_{ct} S(x_c, x_t) \}$

$x_i = m_i^2 / m_W^2$; $\eta_{tt} = 0.574 \pm 0.004$
$\eta_{ct} = 0.47 \pm 0.04$
$\eta_{cc} = 1.38 \pm 0.53$

$f_K = (159.8 \pm 1.4 \pm 0.44)$ MeV, $B_K = 0.86 \pm 0.05 \pm 0.10$
gauss lin.

$B_0 - \overline{B}_0$ Mixing

1) B_d



Measured $\Delta M_{B_d} = 0.489 \pm 0.008 \ ps^{-1}$

(O. Schneider, PDG [illegible])

Using $B_{B_d} f_{B_d}^2 = (1.30 \pm 0.12)(198 \pm 30 \ MeV)^2$

from Lattice calc.

$\eta_{QCD} = 0.55$; $\overline{m}_t(m_t) = 166 \pm 5 \ GeV$

$$|V_{tb}^* V_{td}| = 0.0079 \pm 0.0015$$

2) B_s mixing, ratio: $$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{M_{B_s}}{M_{B_d}} \frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2} \frac{|V_{tb}^* V_{ts}|^2}{|V_{tb}^* V_{td}|^2}$$

with $$\frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2} = 1.15 \pm 0.06 {}^{+0.07}_{-0.00}$$

the exp. lower limit $\Delta M_{B_s} > 13.1 \ ps^{-1}$ (95% CL)

yields $|V_{td}/V_{ts}| < 0.25$

K-system

- domination of $2\pi(I = 0)$ final states

$$\frac{\Gamma_{I=0}}{\Gamma_L + \Gamma_S} \cong 0.99$$

- K_S decays much faster than K_L

$$y = \frac{\Delta\Gamma}{\Gamma} \cong 2$$

- K_S-K_L oscillation frequency
  ≈ decay K_S constant

$$x = \frac{\Delta m}{\Gamma} \cong 0.95$$

- CP violation in the oscillation
  ≈ in the oscillation-decay interplay

$$\cong 10^{-3}$$

B-system

$$m(B) \cong m(K) \times 10^5$$
$$\tau(B) \cong \tau(K) \times 10^{-2}$$

- no dominant final states

- B_S and B_L decay constant differences

B_d	B_d	$y = \frac{\Delta\Gamma}{\Gamma} \cong 5 \times 10^{-3}$	$y = \frac{\Delta\Gamma}{\Gamma} = 5 \times 10^{-3}$
B_s	B_s	$y = \frac{\Delta\Gamma}{\Gamma} \cong 0.1$	$y = \frac{\Delta\Gamma}{\Gamma} = 0.1$

- B_S-B_L oscillations vs. decay constants

B_d	B_d	$x = \frac{\Delta m}{\Gamma} \cong 0.72$	$x_d = \frac{\Delta m}{\Gamma} = 0.72$
B_s	B_s	$x = \frac{\Delta m}{\Gamma} \cong$ big	x_s = very large ~30

$$\Delta m(B_d) \cong \Delta m(K) \times 10^2$$

- CP violation in the oscillation
  expected to be $\cong 10^{-3}$ 10^{-3}

- CP violation in oscillation-decay interplay
  could be $\cong 1$ 1

CP Violation in B decays

contributions from direct
CP violation and from mixing

1) DIRECT CP VIOLATION

Interference between decay
amplitudes, e.g.

$$\Gamma(B^+ \to K^+ \rho^0) \neq \Gamma(B^- \to K^- \rho^0)$$

2) CP VIOLATION IN MIXING

$$\Gamma(\overline{B^0}(t) \to \ell^+ \nu X) \neq \Gamma(B^0(t) \to \ell^- \bar{\nu} X)$$

3) Interference between MIXING
and DECAY

$$\Gamma(\overline{B^0}(t) \to \psi K_s) \neq \Gamma(B^0(t) \to \psi K_s)$$

CP Violation in the B System (2)

The gold-plated decay asymmetry

$$A_{CP}(\overset{(-)}{B}{}^0_d \to \psi K_S) = -\sin 2\beta \frac{x_d}{1+x_d^2}$$

(Time-integrated)

$$A_{CP}(\overset{(-)}{B}{}^0_d \to \pi^+\pi^-) = -\sin 2\alpha \frac{x_d}{1+x_d^2}$$

BaBar	$\sin 2\beta$ =	0.75 ± 0.09
Belle	$\sin 2\beta$ =	0.82 ± 0.12
Average	$\sin 2\beta$ =	0.78 ± 0.08

Unitarity Triangle

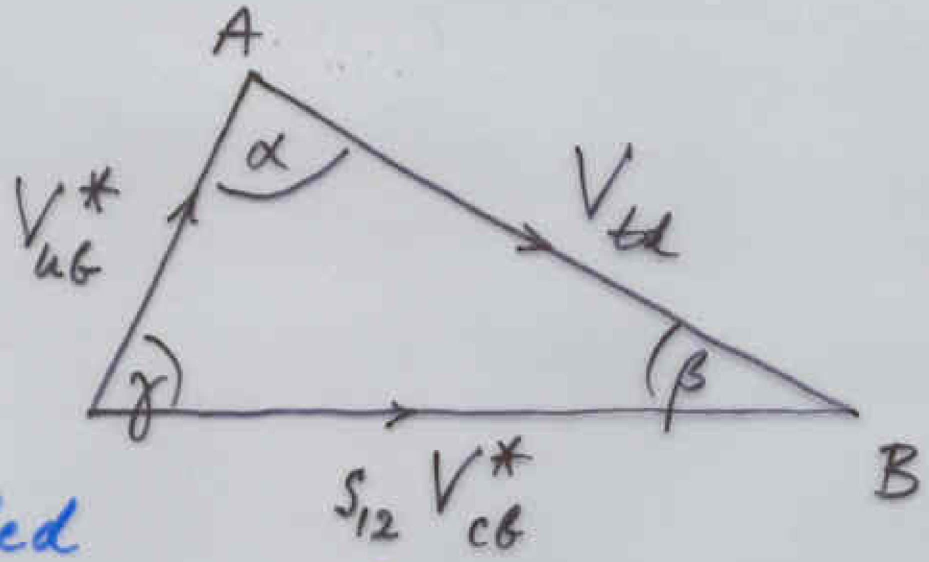
First and third column of V

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

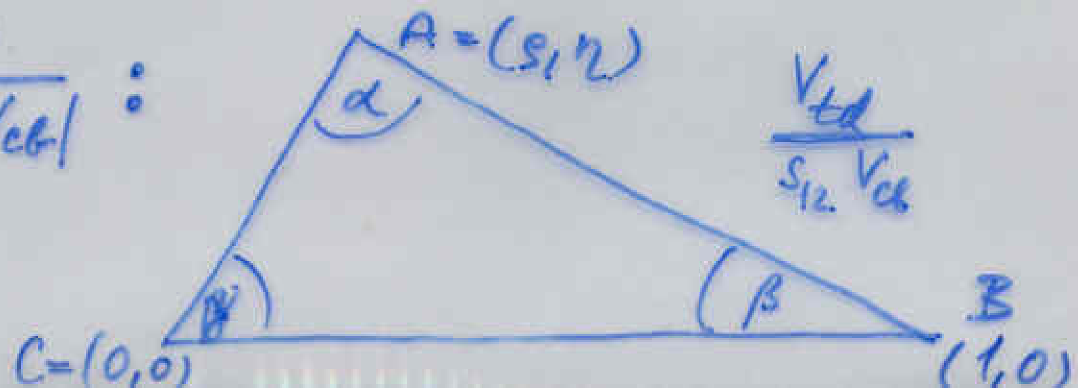
Exp. input: $V_{ud} \approx V_{tb}^* \approx 1$

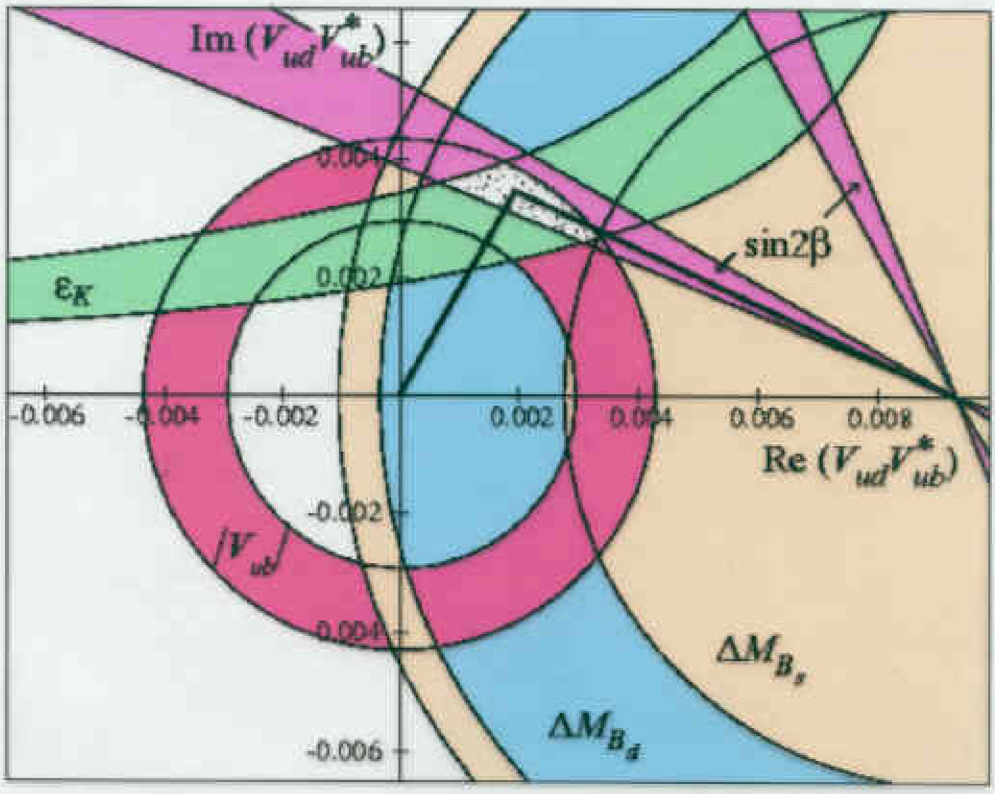
$V_{cd} \approx -s_{12} \approx -\lambda$

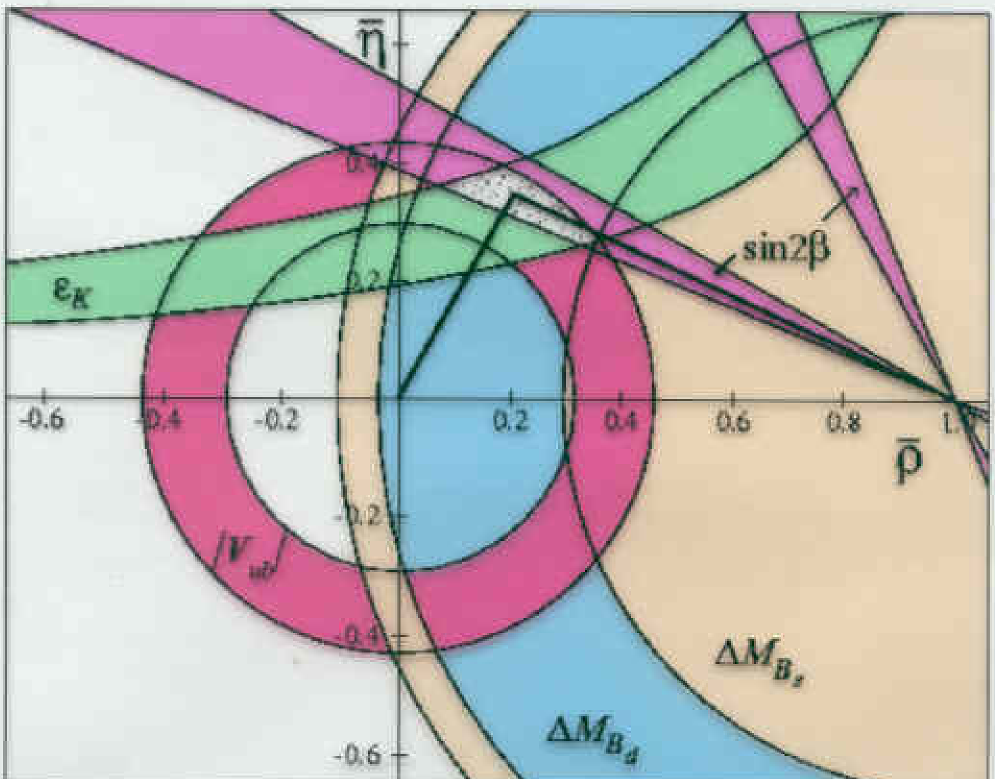
$$V_{ub}^* + V_{td} = s_{12} V_{cb}^*$$



Rescaled by $\frac{1}{|s_{12} V_{cb}|}$:




Im $(V_{ud}V_{ub}^*)$
0.004
0.002
-0.002
-0.004
-0.006
-0.006
-0.004
-0.002
0.002
0.004
0.006
0.008
Re $(V_{ud}V_{ub}^*)$
ε_K
$\sin 2\beta$
$|V_{ub}|$
ΔM_{B_s}
ΔM_{B_d}


$\bar{\eta}$
0.4
0.2
-0.2
-0.4
-0.6
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
$\bar{\rho}$
ε_K
$\sin 2\beta$
$|V_{ub}|$
ΔM_{B_s}
ΔM_{B_d}