Particules Élémentaires, Gravitation et Cosmologie
Année 2007-'08

Le Modèle Standard et ses extensions

CP violation

The 3 Theorems of the flavour sector

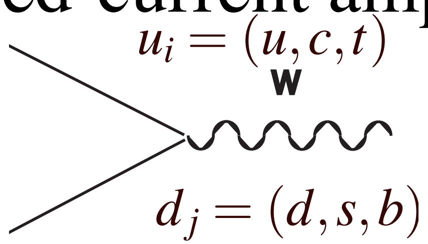
(in spite of the many parameters in $\mathcal{L}$)

$$+\psi_i \lambda_{ij} \psi_j h + h.c.$$

(the 2nd line of page 1)

* Theorem 1: Neglecting ν-masses, L_e, L_μ and L_τ are separately conserved (and CP is exact in the lepton sector)

Theorem 2: In the quarks, all flavor violations reside in the weak charged-current amplitude proportional to a unitary matrix



$$= V_{ij} A \quad \text{with} \quad VV^{+} = \mathbf{1}$$

*Theorem 3: Neglecting ν-masses, CP is violated in as much as V is “intrinsically” complex, i.e. a single phase δ is nonzero

(*with some qualifications - see below)

Theorem 3: Neglecting ν-masses, CP is violated in as much as*
V is "intrinsically" complex, i.e. a single phase δ is nonzero

Proof:

1. Under a CP transformation

$$\psi(\mathbf{x},t) \to i\gamma_2\gamma_0\psi(-\mathbf{x},t)^*$$
$$A_\mu(\mathbf{x},t) \to -A_{\tilde{\mu}}(-\mathbf{x},t)$$
$$Z_\mu(\mathbf{x},t) \to -Z_{\tilde{\mu}}(-\mathbf{x},t)$$
$$W_\mu^+(\mathbf{x},t) \to -W_{\tilde{\mu}}^-(-\mathbf{x},t)$$
$$h(\mathbf{x},t) \to h(-\mathbf{x},t)$$

(a Lorenz index with a ~ requires an overall extra - sign if it is a space index)

so that:

$$particle(\mathbf{p},\mathbf{s}) \to antiparticle(-\mathbf{p},\mathbf{s})$$

*neglecting $\theta G^a_{\mu\nu} G^a_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$ where θ is a parameter which may be set to 0, maybe by a dynamical mechanism (the axion?)

2. Using the previous rules, the overall $\mathcal{L}$ is unchanged* under a CP transformation, except for

$$gW_\mu^+ \bar{u}\gamma_\mu V d + gW_\mu^- \bar{d}\gamma_\mu V^+ u \Rightarrow gW_\mu^- \bar{d}\gamma_\mu V^T u + gW_\mu^+ \bar{u}\gamma_\mu V^* d$$

Counting "intrinsic" phases:

$$N(V_{n\times n}) = n^2$$

$$N(O_{n\times n}) = \frac{n(n-1)}{2}$$

2n quark phases

$U(1)_B$

$$\Rightarrow N(phys.phases) = n^2 - \frac{n(n-1)}{2} - (2n-1) = \frac{1}{2}(n^2 - 3n + 2)$$

n	2	3	4
angles	1	3	6
phys. phases	0	1	3

Q.E.D.

(*actually: $\mathcal{L}(\mathbf{x},t) \to \mathcal{L}(-\mathbf{x},t)$ so that $S = \int d^4x\mathcal{L}$ is unchanged)

CP-violating observables

Useful to "integrate out" the heavy particles (t, W, Z) to obtain an $\mathcal{L}^{eff}$ and repeat the logic just applied to the full SM Lagrangian

(a low energy experiment is insensitive to "short distance" physics)

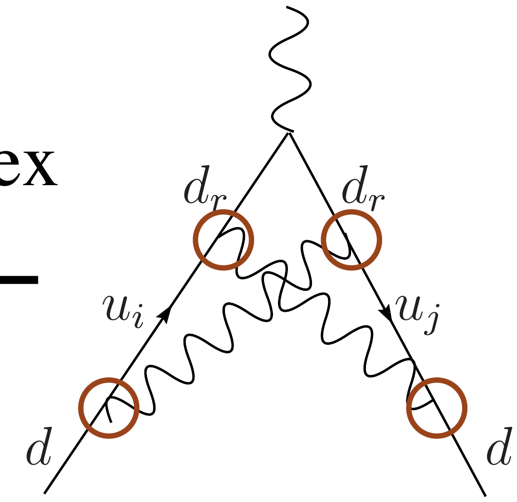
Which operators can give rise to observable CP-violation?

⇒ In order of increasing dimensionality (= decreasing relevance):

dim 5: quarks Electric Dipole Moments

$$\mathcal{L}^{eff} = \mu \bar{q}_L \sigma_{\mu\nu} q_R F^{\mu\nu} + m \bar{q}_L q_R$$ with μ/m complex

$$\Rightarrow d_{neutron}(SM) \approx 10^{-31} e \cdot cm$$



$$d_{neutron}(exp) \leq 6 \cdot 10^{-26} e \cdot cm \approx 10^{-11} \frac{e}{2m_N}$$

[$d_e(SM) \approx 0$ against

$d_e(exp) = (0.07 \pm 0.07) 10^{-26} e \cdot cm \approx 10^{-16} \mu_B$]

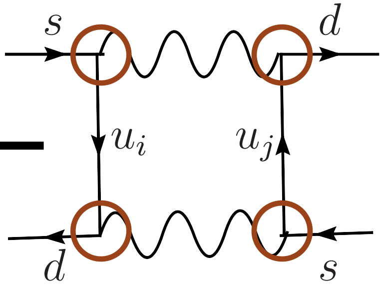
CP-violating observables (continued)

dim 6: FCNC $(\bar{q}q)(\bar{q}q)$ interactions

Consider, e.g., strangeness changing interaction

$$\mathcal{L}_{eff}^{(\Delta S\neq 0)} = \mathcal{L}_{eff}^{(\Delta S=2)} + \mathcal{L}_{eff}^{(\Delta S=1)} + \mathcal{L}_{eff}^{(\Delta S=1;semilept.)} + h.c$$

$$\mathcal{L}_{eff}^{(\Delta S=2)} = A(\bar{s}_L\gamma_\mu d_L)(\bar{s}_L\gamma_\mu d_L)$$



$$\mathcal{L}_{eff}^{(\Delta S=1)} = \Sigma_q B_q(\bar{s}_L\gamma_\mu d_L)(\bar{q}\gamma_\mu q) \quad q = u,d$$

$$\mathcal{L}_{eff}^{(\Delta S=1;semilept.)} = \Sigma_l C_l(\bar{s}_L\gamma_\mu d_L)(\bar{l}\gamma_\mu l) \quad l = e,\mu,\nu$$

$m\bar{s}_L s_R$

A relative phase between:

1. A and any of the B_q $(\phi(A) \neq 2\phi(B))$
2. the B_q themselves
3. A and any the C_l

is *genuine* and gives in principle an observable effect

Case 1 (*indirect*) ε_K $\Rightarrow \Delta S = 2/\Delta S = 1$

$$|\eta_{+-}| \equiv |\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}| = (2.236 \pm 0.007)10^{-3}$$

$$|\eta_{00}| \equiv |\frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}| = (2.225 \pm 0.007)10^{-3}$$

$$\delta_K = \frac{\Gamma(K_L \to \pi^- l^+ \nu) - \Gamma(K_L \to \pi^+ l^- \bar{\nu})}{\Gamma(K_L \to \pi^- l^+ \nu) + \Gamma(K_L \to \pi^+ l^- \bar{\nu})} = (3.32 \pm 0.06)10^{-3}$$

(The 2π system in an S-wave is a CP eigenstate because of Bose statistic)

It follows that $CP\, \mathcal{H}\, CP^{-1} \neq \mathcal{H}$

and that K_L, K_S are not quite the same as K_1, K_2 of lecture 6, but rather

$$|K_{L,S}> = \frac{1}{\sqrt{|p|^2 + |q|^2}}(p|K^0> \pm q|\bar{K}^0>)$$

$$|\frac{q}{p}| = |\frac{1-\varepsilon_K}{1+\varepsilon_K}| \neq 1$$

$$|\varepsilon_K| = (2.232 \pm 0.007)10^{-3}$$

Case 2 (*direct*) ε'_K $\Rightarrow \Delta S = 1$

$$\eta_{00} = \varepsilon_K - 2\varepsilon'_K \qquad \eta_{+-} = \varepsilon_K + \varepsilon'_K$$

$$1 - |\eta_{00}/\eta_{+-}| = (5.01 \pm 0.78)10^{-3} \qquad Re(\varepsilon'_K/\varepsilon_K) = (1.66 \pm 0.26)10^{-3}$$

Case 3 not observed so far ($K_L \to \pi^0 + \nu\bar{\nu}$)

$\Rightarrow$ CP-violations also observed in ΔB=2/ΔB=1 and in ΔB=1

Case 1 (*indirect*)

$$\frac{d\Gamma/dt(\bar{B}_d(t) \to \psi K_S) - d\Gamma/dt(B_d(t) \to \psi K_S)}{d\Gamma/dt(\bar{B}_d(t) \to \psi K_S) + d\Gamma/dt(B_d(t) \to \psi K_S)} = \sin 2\beta \sin(\Delta m\, t)$$

$$\sin 2\beta = 0.696[+0.017 - 0.029]$$

Case 2 (*direct*)

$$\frac{\Gamma(\bar{B}_d \to K^-\pi^+) - \Gamma(B_d \to K^+\pi^-)}{\Gamma(\bar{B}_d \to K^-\pi^+) + \Gamma(B_d \to K^+\pi^-)} = -0.095 \pm 0.013$$

and in other channels as well

The Flavour Precision Tests 2

(⇒ = CP-violating measurements)

(ε'_K not included because of uncertain matrix element)

	Observable	elementary process	exp. error	theor. error
⇒	ϵ_K	$\bar{s}d \to \bar{d}s$	1%	$10 \div 15\%$
	$K^+ \to \pi^+ \bar{\nu}\nu$	$s \to d\ \bar{\nu}\nu$	70%	3%
⇒	$K^0 \to \pi^0 \bar{\nu}\nu$	$s \to d\ \bar{\nu}\nu$		1%
	Δm_{Bd}	$\bar{b}d \to \bar{d}b$	1%	25%
⇒	$A_{CP}(B_d \to \Psi K_S)$	$\bar{b}d \to \bar{d}b$	5%	$< 1\%$
	$B_d \to X_s + \gamma$	$b \to s + \gamma$	10%	$5 \div 10\%$
	$B_d \to X_s + \bar{l}l$	$b \to s + \bar{l}l$	25%	$10 \div 15\%$
	$B_d \to X_d + \gamma$	$b \to d + \gamma$		$10 \div 15\%$
	$B_d \to \bar{l}l$	$b\bar{d} \to \bar{l}l$		10%
	$B_d \to X_d + \bar{l}l$	$b \to d + \bar{l}l$		$10 \div 15\%$
	Δm_{Bs}	$\bar{b}s \to \bar{s}b$	$< 1\%$	25%
⇒	$A_{CP}(B_s \to \Psi\phi)$	$\bar{b}s \to \bar{s}b$		1%
	$B_s \to \bar{l}l$	$b\bar{s} \to \bar{l}l$		10%

A remarkable list of <u>calculable loop effects</u>, with virtual Ws

All agreeing with the SM (~2000→)

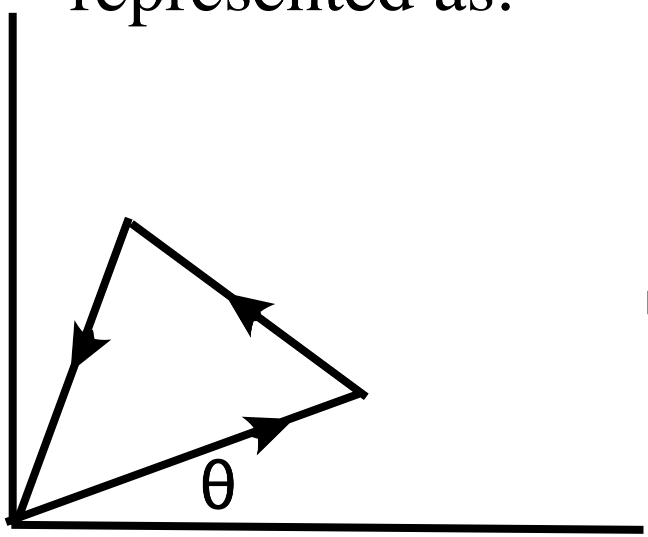
The Flavour tests 2

$$VV^{+} = \mathbf{1}$$

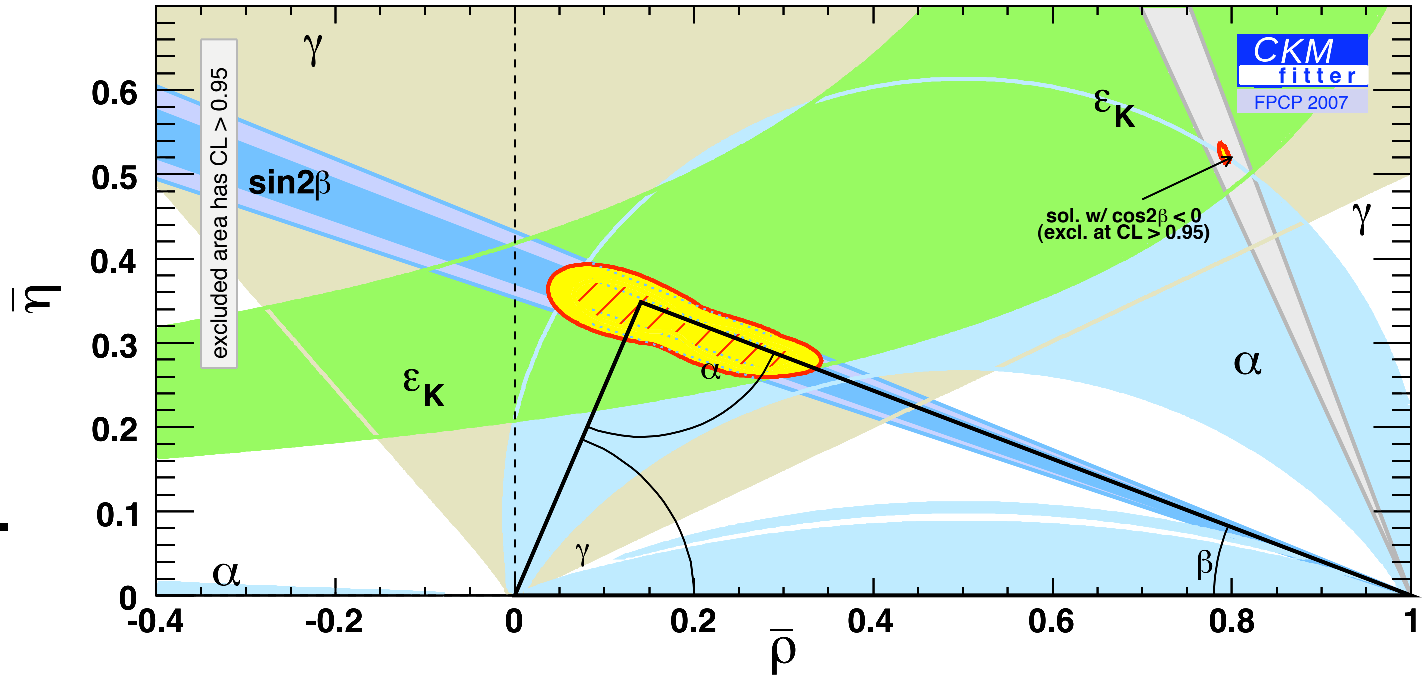
in particular:

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

represented as:



(the angle θ has no physical meaning)



(only using CP-violating measurements)

a non degenerate triangle = CP violation

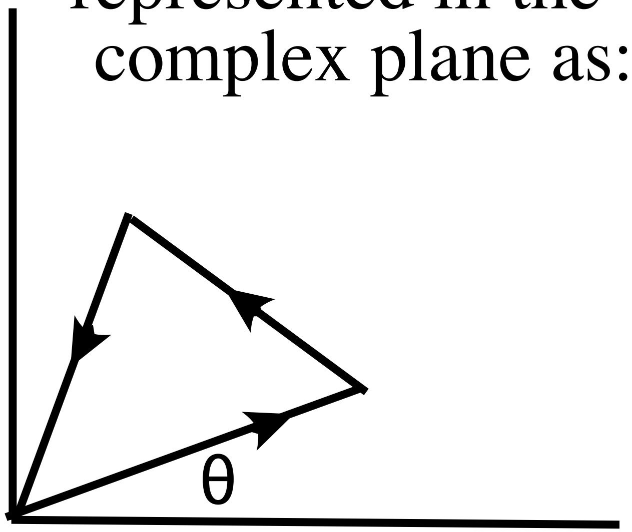
The Flavour tests 1

$$VV^{+} = \mathbf{1}$$

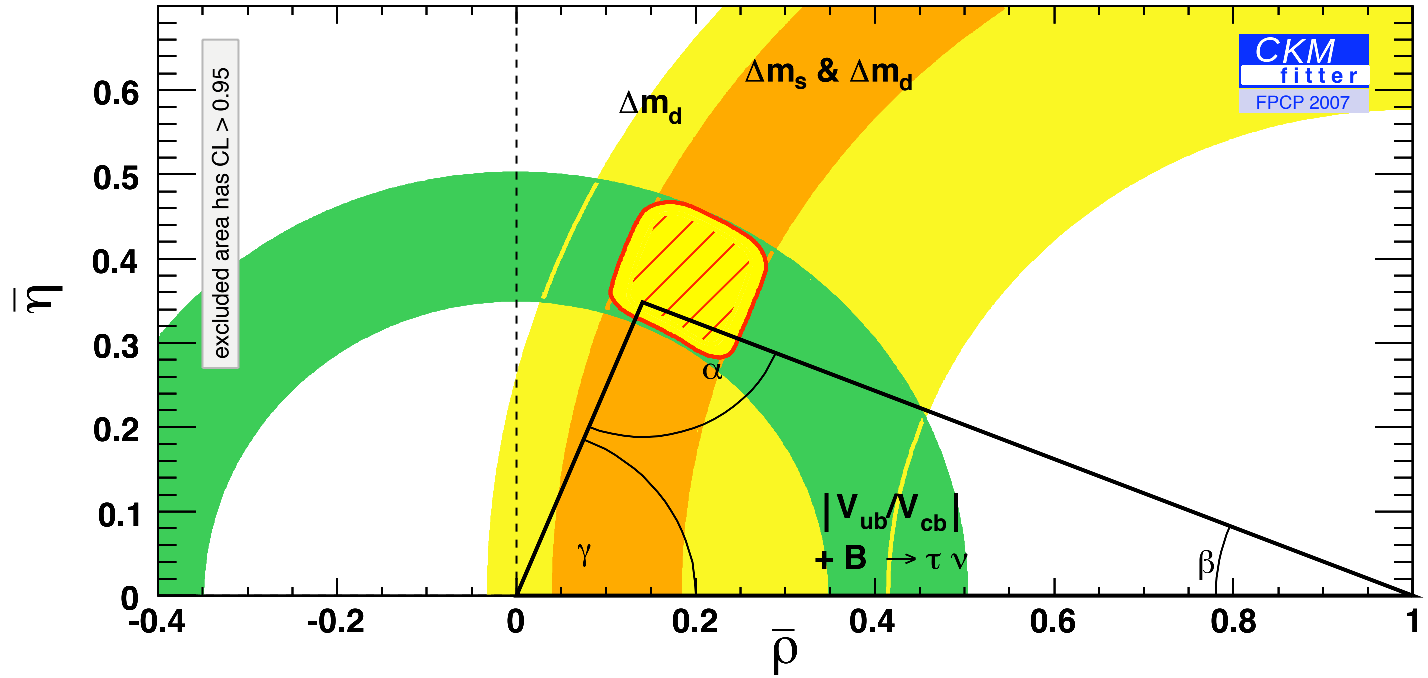
in particular:

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

represented in the complex plane as:



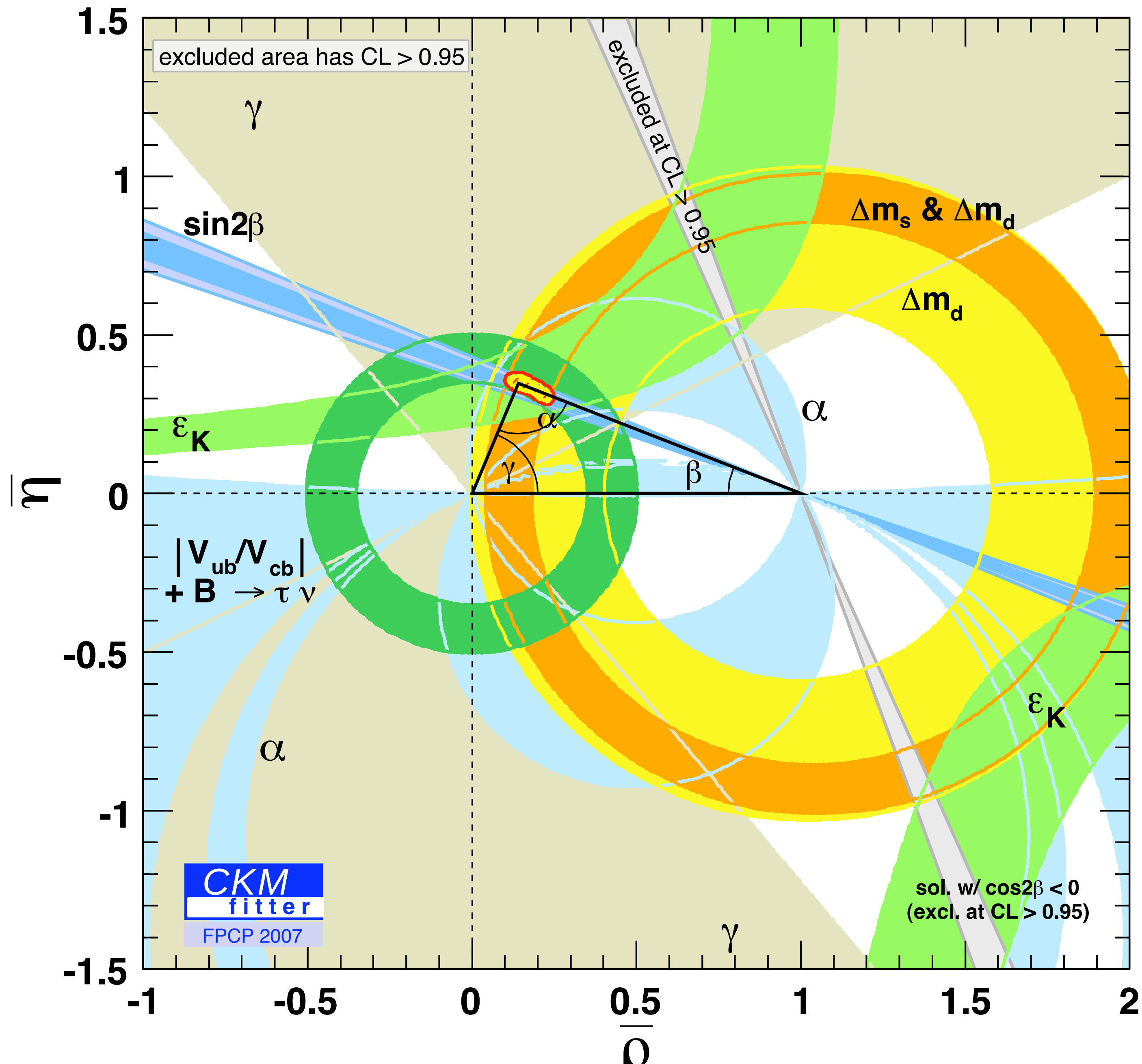
(the angle θ has no physical meaning)



(only using CP-conserving measurements)

a non degenerate triangle
= CP violation (see below)

The overall fit



The CKM description of flavour proven right

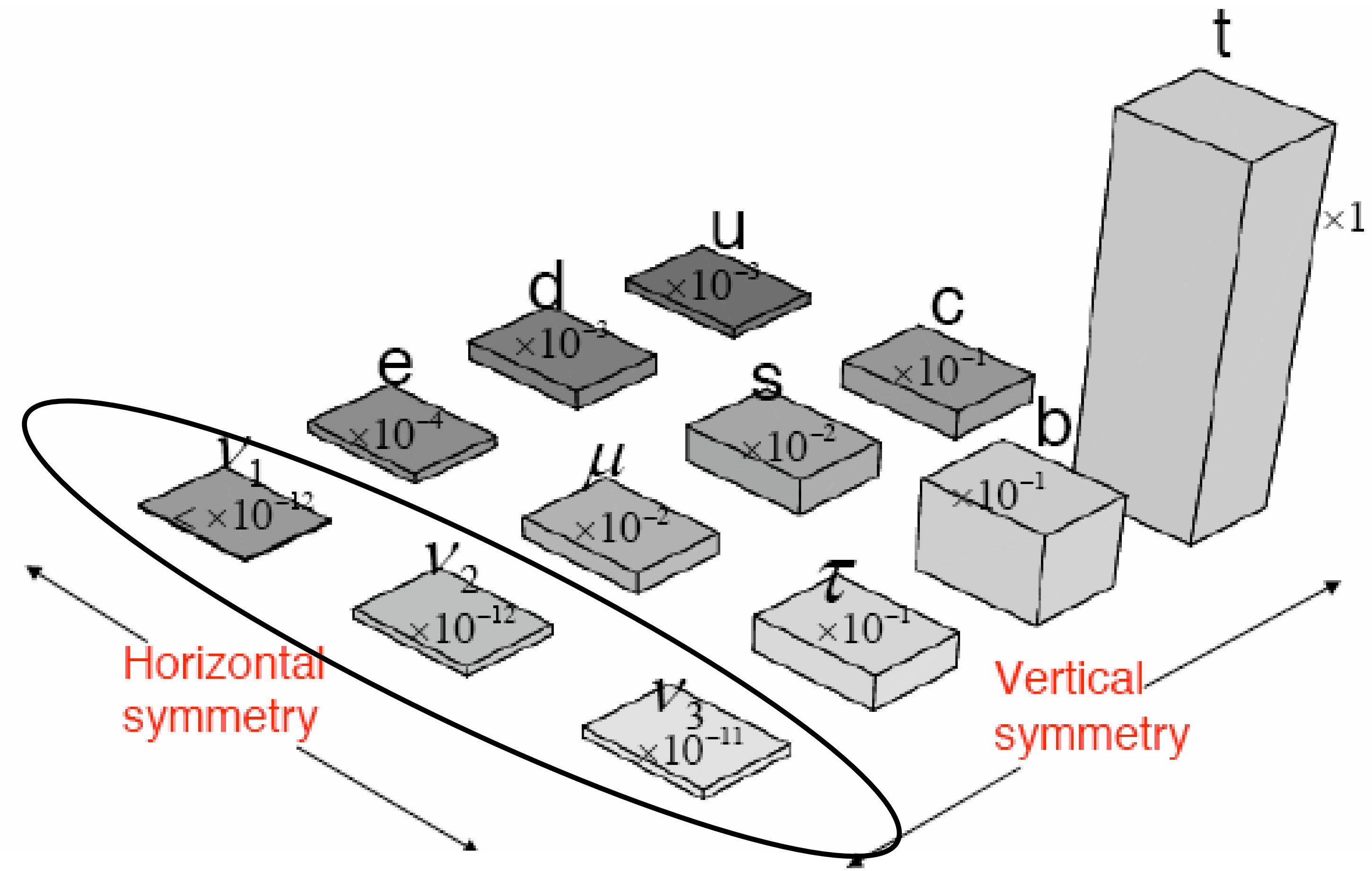
A summary of the present status

1 - We know the SM works quantitatively in the full quark sector (A major change in the 2000's)

2 - If there are other degrees of freedom at the Fermi scale carrying flavour (e.g. the s-fermions), unlikely that there be no extra flavour phenomena observable at some level

3 - We know all the 10 parameters in the quark sector (6 +3+1) and 7 (3+2+2) out of the 10/12 (6 +3 +1/3) in the lepton sector (but no hard theory for them)

The persistent flavour puzzle



Many attempts

Can one claim any real success?