Particules Élémentaires, Gravitation et Cosmologie
Année 2007-'08

Le Modèle Standard et ses extensions

The Flavour Sector

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} \not{D} \psi$$ *The gauge sector (1)*

$$+\psi_i \lambda_{ij} \psi_j h + h.c.$$ *The flavour sector (2)*

$$+|D_\mu h|^2 - V(h)$$ *The EWSB sector (3)*

$$+N_i M_{ij} N_j$$ *The ν-mass sector (4) (if Majorana)*

The quadrant of nature whose laws can be summarized in one page with absolute precision and empirical adequacy

One century to develop it, from Maxwell on

Can it be the end of the story?

The 3 Theorems of the flavour sector

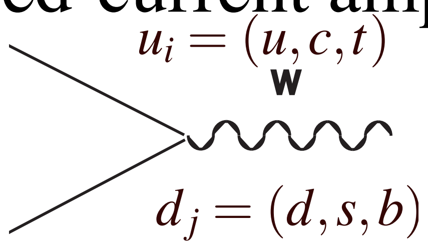
(in spite of the many parameters in $\mathcal{L}$)

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

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

Proof: $$\mathcal{L}^{(lept)} = i\bar{L}_i \not{D} L_i + i\bar{e}_i^c \not{D} e_i^c + e_i \lambda_{ij}^e e_j^c (v+h) + (N - terms)$$

Since $\lambda^e = V_L^T \lambda_d^e V_R$ with "d" for "diagonal"

can redefine

$$V_R e^c \Rightarrow e_{ph}^c \qquad V_L L = \begin{pmatrix} V_L \nu \\ V_L e \end{pmatrix} \Rightarrow \begin{pmatrix} \nu_{ph} \\ e_{ph} \end{pmatrix} \equiv L_{ph}$$

so that

$$\mathcal{L}^{(lept)} = i\bar{L}_{ph} \not{D} L_{ph} + i\bar{e}_{ph}^c \not{D} e_{ph}^c + e_{ph}^T \lambda_d^e e_{ph}^c (v+h) + (N - terms)$$

$$\to (m_e e e_c + m_\mu \mu \mu_c + m_\tau \tau \tau_c)(1 + h/v)$$

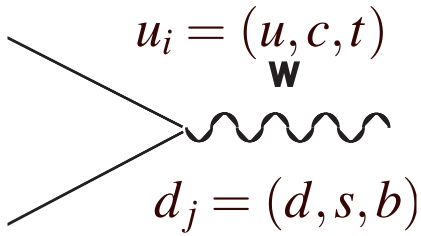
Essential that ν and e are rotated simultaneously, since

$$Z_\mu \bar{e} \gamma_\mu e, \quad Z_\mu \bar{\nu} \gamma_\mu \nu$$

but also $W_\mu \bar{e} \gamma_\mu \nu$

(*up to very small quantum effects, (perhaps relevant in the early universe)

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



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

Proof:

$$\mathcal{L}^{(quarks)} = i\bar{Q}\,\not{D}Q + i\bar{u^c}\,\not{D}u^c + i\bar{d^c}\,\not{D}d^c$$

$$+ u^T U_L^T \lambda^u_d U_R u^c (v+h) + d^T D_L^T \lambda^d_d D_R d^c (v+h)$$

hence, this time, by going to the physical basis, all diagonal currents, J_μ^{em} and J_μ^Z , remain unchanged, <u>but not</u>

$$W_\mu \bar{u} \gamma_\mu d \Rightarrow W_\mu \bar{u}_{ph} U_L D_L^{+} \gamma_\mu d_{ph}$$

$$= W_\mu \bar{u}_{ph} V \gamma_\mu d_{ph} \quad \text{with} \quad V = U_L D_L^{+}$$

(Note the asymmetry between quarks and leptons!)

Testing the Theorems

Qualitative, but highly significant:

L_e, L_μ and L_τ -Violations

$BR(\mu \to e + \gamma) < 1.2 \cdot 10^{-11}$

$BR(\mu \to e\bar{e}e) < 1.0\ 10^{-12}$

$CR(\mu \to e\ in\ Ti) < 6.1\ 10^{-13}$

and weaker but still significant in the τ case

(with ν-masses included)

$$\mathcal{L}_{\mu \to e+\gamma} \approx A(\bar{\mu}\sigma_{\nu\mu}e)F_{\nu\mu}$$

$$A < e\frac{\alpha}{\pi}\frac{m_\mu}{m_W^2}\frac{m_\nu}{m_W}$$

$$BR|_{SM} \approx 10^{-50}$$

Quantitative: (highly interrelated)

$VV^+ = \mathbf{1}$

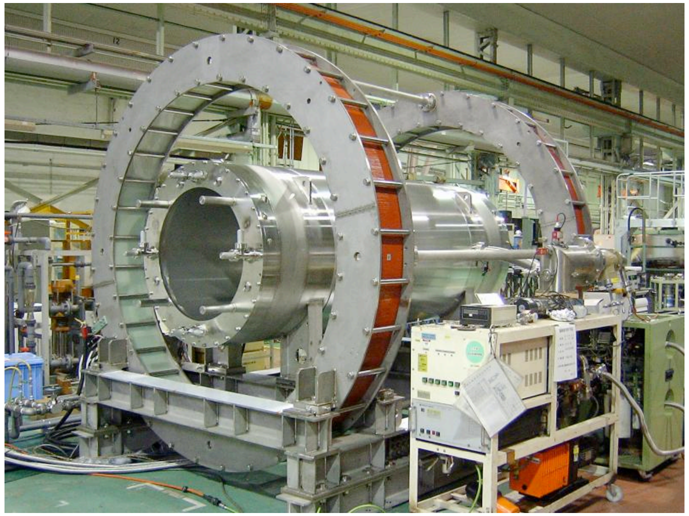
Calculable Flavour Changing Neutral Current processes (FCNC)

CP-asymmetries (see next lecture)

(A major change in the 2000's)

My own favorite test of Flavour Physics

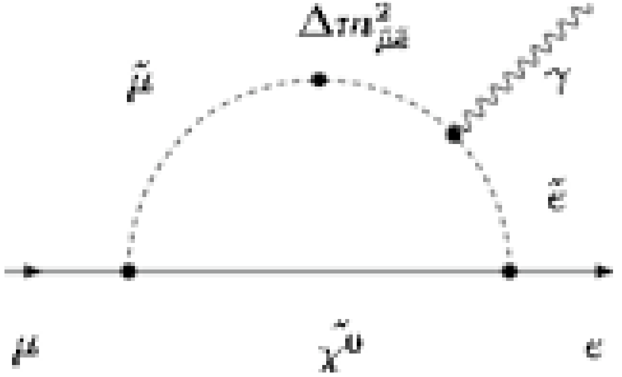
$$\mu \to e + \gamma$$



(not only the LHC)

Current limit $BR(\mu \to e + \gamma) < 1.2 \cdot 10^{-11}$

An experiment, MEG, just starting at PSI aiming at a factor of 100 better sensitivity



Not in the SM!

Two good reasons to believe in it:

1. Unification
2. Neutrino oscillations

$VV^+ = \mathbf{1}$

$\Sigma_i |V_{ai}|^2 = 1 \quad a = 1,2,3$ 3 rel.s (Type I)

$\Sigma_i V_{ai} V^*_{ib} = 0 \quad a \neq b$ 6 rel.s (Type II)

Type I: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(11)$

(about 1 ppm precision!)

$N \to N' + e + \nu \Rightarrow |V_{ud} f^{ud}(0)|$ $|V_{ud}| = 0.97377(27)$

$d \to u + e + \bar{\nu}$ (0.3 ppm)

$K \to \pi + e + \nu \Rightarrow |V_{us} f^{us}(0)|$ $|V_{us}| = 0.2257(21)$

$s \to u + e + \bar{\nu}$ (1%)

$B \to X_u + l + \bar{\nu} \Rightarrow |V_{ub}|$ $|V_{ub}| = 4.31(30) \cdot 10^{-3}$

$b \to u + l + \bar{\nu}$ (10%)

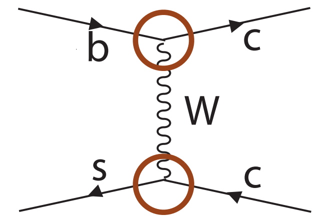
isospin, SU(3) ~ conserved in QCD

(about 1% precision for the second row, when $u \to c$)

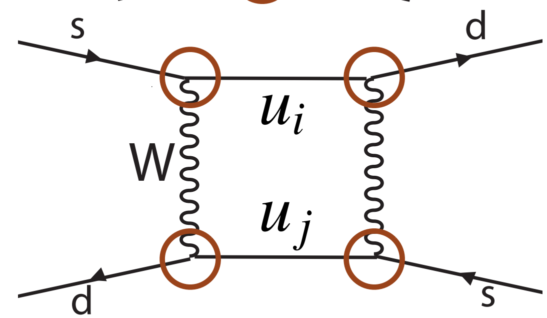
FCNC processes (genuine and calculable)

1. Interesting because absent at tree level
   (hence sensitive to new physical phenomena !?)
   (Theor. 2: only the W-int.s produce flavor change, not the Z!)

2. Genuine? E.g.: $b\bar{s} \longrightarrow c\bar{c}$? No



$\bigcirc = V_{CKM}$



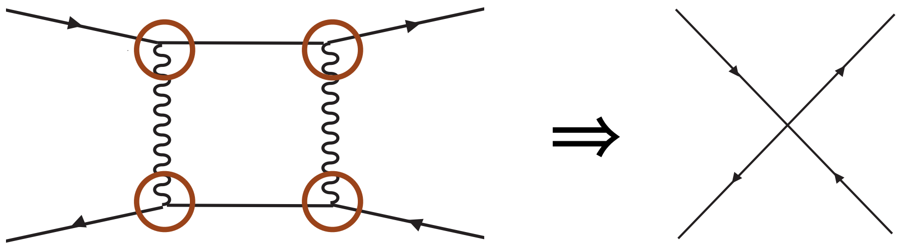
3. Calculable? E.g.: $s\bar{d} \longrightarrow d\bar{s}$?

Yes this diagram, but how about its gluon dressing?
It depends on the typical momentum of the int. lines:
If small (≤ 1 GeV) not calculable, if large yes.
(asymptotic freedom of QCD)

$\Rightarrow$ $\Delta m_{K\bar{K}}$ (the "real part") no
ε_K (the "imag. part") yes (see next lecture)

The actual computation of a FCNC process

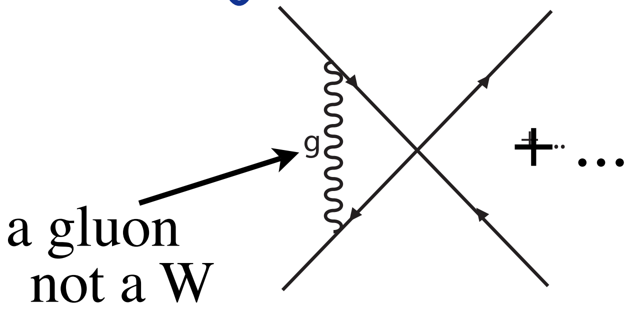
1. The "short-distance" EW loop



: an *effective operator* $\widehat{O}$ with a known coefficient C

(a low energy experiment is insensitive to the internal structure of the loop)

2. The gluon dressing



:generally divergent

$$\Rightarrow C(\alpha_S \log\frac{M}{m}, \alpha_S) \qquad M = M_W, m_t \quad m = m_c, m_b$$

Need to re-sum all orders (RG) in $\alpha_S \log\frac{M}{m}$

3. The "matrix element" for the actual physical process

$$A_{i\to f} = C < f|\widehat{O}|i >$$

Need some non perturbative technique or some exp. data

The Flavour Precision Tests 1

($\Rightarrow$ = CP-conserving measurements)

	Observable	elementary process	exp. error	theor. error
	ϵ_K	$\bar{s}d \to \bar{d}s$	1%	$10 \div 15\%$
$\Rightarrow$	$K^+ \to \pi^+ \bar{\nu}\nu$	$s \to d\ \bar{\nu}\nu$	70%	3%
	$K^0 \to \pi^0 \bar{\nu}\nu$	$s \to d\ \bar{\nu}\nu$		1%
$\Rightarrow$	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%	$< 1\%$
$\Rightarrow$	$B_d \to X_s + \gamma$	$b \to s + \gamma$	10%	$5 \div 10\%$
$\Rightarrow$	$B_d \to X_s + \bar{l}l$	$b \to s + \bar{l}l$	25%	$10 \div 15\%$
	$B_d \to X_d + \gamma$	$b \to d + \gamma$		$10 \div 15\%$
	$B_d \to \bar{l}l$	$\bar{b}d \to \bar{l}l$		10%
	$B_d \to X_d + \bar{l}l$	$b \to d + \bar{l}l$		$10 \div 15\%$
$\Rightarrow$	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%

(When blank, data still lacking)

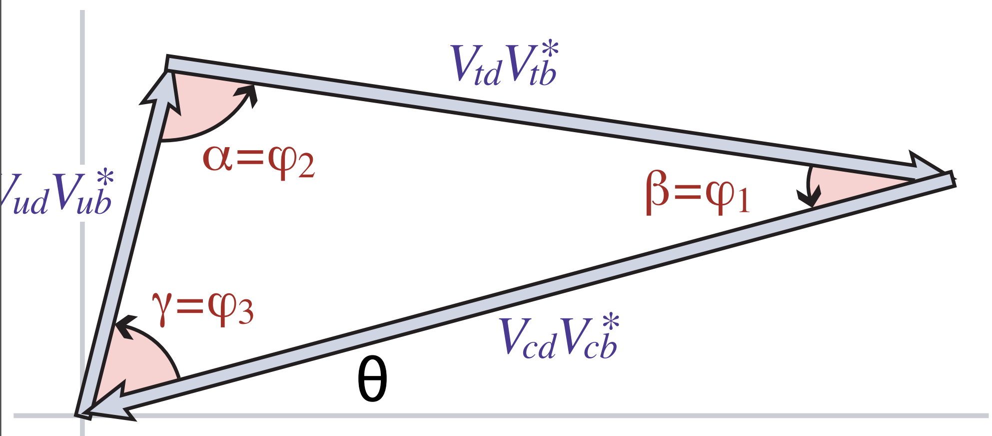
The Flavour tests 1

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

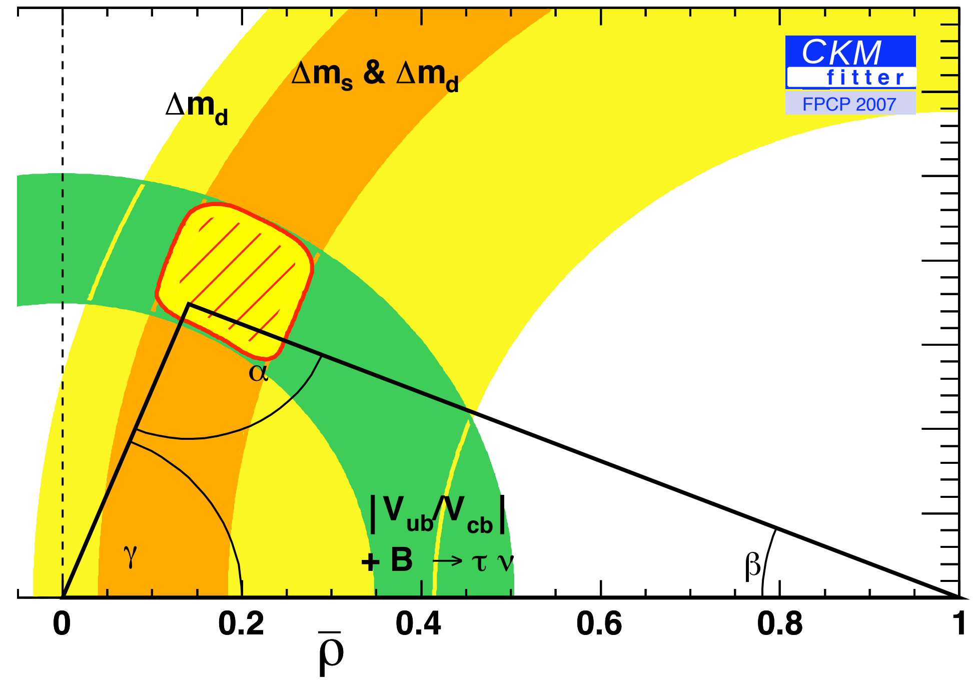
in particular:

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

represented in the complex plane as:



(the angle θ has no physical meaning, only the shape has it)



(only using CP-conserving measurements)

a non degenerate triangle = CP violation (see below)

For an overall picture of flavour physics,

need to discuss CP as well

See this afternoon lecture