

Corfu Summer School and
Workshop

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Flavour Physics

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Flavour in the Standard Model (SM)

$$G_{\text{SM}} = \text{SU}(2)_L \times \text{U}(1) \times \text{SU}(3)_C$$

Fermions in the SM:

Quarks: $\begin{bmatrix} u^o \\ d^o \end{bmatrix}_L ; \begin{bmatrix} c^o \\ s^o \end{bmatrix}_L ; \begin{bmatrix} t^o \\ b^o \end{bmatrix}_L \rightarrow \text{doublets}$

$u_R^o, d_R^o \quad c_R^o, s_R^o \quad t_R^o, b_R^o \rightarrow \text{singlets}$

Leptons: $\begin{bmatrix} \nu_1^o \\ e^o \end{bmatrix}_L ; \begin{bmatrix} \nu_2^o \\ \mu^o \end{bmatrix}_L ; \begin{bmatrix} \nu_3^o \\ \tau^o \end{bmatrix}_L \rightarrow \text{doublets}$

Neutrinos are strictly massless in the SM.

Simplist extension of the SM which allows for neutrino masses:

Add right-handed neutrinos

$$\nu_{Ri} \rightarrow$$

Seesaw mechanism

Important feature of the SM :

In the SM, there ^{are} ~~no~~ fermion mass terms, prior to spontaneous gauge symmetry breaking :

They are forbidden by the gauge symmetry.

For example :

$$m_{ij} \bar{d}_L^o i \bar{d}_R^o j \rightarrow \text{forbidden}$$

↓ ↓
 doublet singlet

Similarly for

$$\bar{u}_L^o i \bar{u}_R^o j$$

$$\bar{e}_L^o i \bar{e}_R^o j$$

Generation of quark and charged lepton masses, through Yukawa interactions

$$(Y_d)_{ij} \begin{bmatrix} \bar{u}_L^\circ & \bar{d}_L^\circ \end{bmatrix}_i d_R^j \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix}$$

Upon gauge symmetry breaking fermion masses are generated

$$\mathcal{V} (Y_d)_{ij} \bar{d}_L^\circ_i d_R^j + h.c.$$

Similarly, for up quarks and charged leptons:

$$(Y_u)_{ij} \begin{bmatrix} u_L^\circ & d_L^\circ \end{bmatrix}_i u_R^j \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix}$$

$$\mathcal{V} (Y_e)_{ij} \bar{l}_L^\circ_i l_R^j + h.c.$$

Neutrino Masses

In the SM, neutrinos are strictly massless.

- No Dirac mass

$$\overline{\nu_L} \nu_R$$

Since no ν_R are introduced

- No Majorana mass

$$\nu_L^T C \nu_L$$

- at tree level since no Higgs triplets are introduced

- cannot arise in higher orders

due to exact B-L conservation

$m_\nu \neq 0 \Rightarrow$ New Physics
Beyond the SM

Generation of quark mixing in charged weak currents :

Diagonalization of quark masses :

$$U_L^{u^+} M_u U_R^u = \text{diag.}(m_u, m_c, m_t)$$

$$U_L^{d^+} M_d U_R^d = \text{diag.}(m_d, m_s, m_b)$$

$$(\bar{u}^0 \bar{c}^0 \bar{t}^0)_L \gamma_\mu \begin{bmatrix} d^0 \\ s^0 \\ b^0 \end{bmatrix}_L W^\mu \rightarrow [\bar{u} \bar{c} \bar{t}] \gamma_\mu V_{CKM} \begin{bmatrix} d \\ s \\ b \end{bmatrix} W^\mu$$

\downarrow
weak basis

\downarrow
mass eigenstate basis

$$V_{CKM} = U_L^{u^+} U_L^d$$

$$(\bar{u} \bar{c} \bar{t}) \gamma_\mu \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} W^\mu$$

In the SM, V_{CKM} is a 3×3 unitary matrix

Rephasing of quark fields

Even after diagonalization of quark mass matrices, leading to :

$$m_u \bar{u} u + m_c \bar{c} c + m_t \bar{t} t + \\ + m_d \bar{d} d + m_s \bar{s} s + m_b \bar{b} b$$

one has still the freedom to rephase the quark fields

$$u \rightarrow u' = u e^{i\gamma_u} \\ d \rightarrow d' = d e^{i\gamma_d}$$

Obviously, the quark mass terms remain invariant under "rephasing"

$$\bar{u}_L \gamma_\mu V_{ud} d W^\mu \rightarrow \bar{u}'_L \gamma_\mu V'_{ud} d'_L W^\mu$$

$$V'_{ud} = \exp i[\gamma_u - \gamma_d] V_{ud}$$

- Individual arguments of V_{ij}^{CKM} have no physical meaning.
- We are assuming "implicitly" no degeneracy of quark masses

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Physical quantities should be rephasing invariant!

Simpler rephasing invariant functions
of $(V_{CKM})_{ij}$:

$|V_{ij}| \rightarrow$ moduli

$$Q_{\alpha i \beta j} = V_{\alpha i} V_{\beta j} V_{\alpha j}^* V_{\beta i}^*$$

Invariant quantity

Example : $Q_{uscb} = V_{us} V_{cb} V_{ub}^* V_{cs}^*$

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

Diagram showing the CKM matrix with red arrows indicating diagonal elements and green arrows indicating off-diagonal elements.

Invariants of higher order may in general be written as functions of quartets and moduli. For example :

$$V_{\alpha i} V_{\beta j} V_{\gamma k} V_{\alpha j}^* V_{\beta k}^* V_{\gamma i}^* = \frac{Q_{\alpha i \beta j} Q_{\beta i \gamma k}}{|V_{\beta i}|^2}$$

Invariant setit

Constraints of unitarity :

In the SM with three generations, V^{CKM} is a 3×3 unitary matrix.

Consider orthogonality of the first two rows of V^{CKM} :

$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

Multiplying by $V_{us}^* V_{cs}$ and taking imaginary parts, one obtains

$$\text{Im } Q_{udcs} = - \text{Im } Q_{ubcs}$$

In an analogous way, one can show that the imaginary parts of all invariant quartets are equal up to their sign.

$\text{Im } Q$ gives the strength of CP violation in the SM

The six orthogonality relations for the three generation CKM matrix :

$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

$$\rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \quad \text{db}$$

$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

$$\rightarrow V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0 \quad \text{ut}$$

$$V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0$$

It can be shown that, due to 3×3 unitarity, all triangles have the same area and furthermore:

$$\text{Area of triangle} = \frac{|\text{Im } Q|}{2}$$

What is the strength of CP violation in the SM?

$$|\mathcal{V}_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}; \lambda = .22$$

$$|\text{Im } Q| = |\text{Im}(\mathcal{V}_{ud} \mathcal{V}_{cb} \mathcal{V}_{ub}^* \mathcal{V}_{cd}^*)| \\ \approx \lambda^6 |\sin \delta|$$

$$\delta = \arg(-\mathcal{V}_{ud} \mathcal{V}_{cb} \mathcal{V}_{ub}^* \mathcal{V}_{cd}^*)$$

Maximal CP violation

What is the maximal value of $|Im Q|$ if one forgets the experimental knowledge of $|V_{ij}^{CKM}|$?

It can be readily seen that the maximal value of $|Im Q|$ is obtained for :

$$V = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{i2\pi/3} & \bar{e}^{-i2\pi/3} \\ 1 & \bar{e}^{-i2\pi/3} & e^{i2\pi/3} \end{bmatrix}$$

leading to

$$|Im Q| = \frac{1}{6\sqrt{3}} \approx .096$$

The question of CP violation

- A pure gauge Lagrangian is necessarily CP-invariant
(Grimus & Rehder 1997)
- The scalar potential of the SM, with only one Higgs doublet, necessarily conserves CP. Furthermore, no spontaneous CP violation can take place in the SM.



Therefore, in the SM, CP violation can only arise from the simultaneous presence of Yukawa interactions and gauge interactions

CP transformation properties are dictated by the electromagnetic interactions and the diagonal, real mass terms :

$$(CP) W^{+\mu}(t, \vec{r})(CP)^+ = -e^{i\beta_W} W_\mu^-(t, -\vec{r})$$

$$(CP) u_\alpha(t, \vec{r})(CP)^+ = e^{i\beta_\alpha} \gamma^0 C \bar{u}_\alpha^T(t, -\vec{r})$$

$$(CP) d_K(t, \vec{r})(CP)^+ = e^{i\beta_K} \gamma^0 C \bar{d}_K^T(t, -\vec{r})$$

Invariance of the charged weak current interactions constrains V_{CKM} elements to satisfy the following constraint :

$$V_{\alpha K}^* = e^{i(\beta_W + \beta_K - \beta_\alpha)} V_{\alpha K}$$

We have used :

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left[W_\mu^+ \bar{u}_L \gamma^\mu d_L + W_\mu^- \bar{d}_L \gamma^\mu v_L^+ \right]$$

The constraint on $V_{\alpha k}$ can always be satisfied if one considers a single matrix element of V , since $\mathcal{F}_W, \mathcal{F}_\alpha, \mathcal{F}_k$ are arbitrary.

However, this constraint on $V_{\alpha k}$ implies that "invariant quartets" of V^{CKM} have to be real in order for CP invariance to be satisfied

Theorem -

In general, there is CP violation in the SM if and only if any of the rephasing-invariant functions of the CKM matrix is not real

In the SM :

$$\text{Im } Q \neq 0 \Leftrightarrow \text{CP violation}$$

An alternative way of seeing why in the SM for 2 generations there is no CP violation:

$$\begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix}$$

One can construct a rephasing invariant quantity:

$$Q = V_{ud} V_{cs} V_{us}^* V_{cd}^*$$

But consider orthogonality of the two rows:

$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* = 0$$

Multiplying by $V_{us}^* V_{cs}$:

$$V_{ud} V_{cs} V_{us} V_{cd}^* + |V_{us}|^2 |V_{cs}|^2 = 0$$

$\text{Im } Q = 0$

Parameter Counting

In the SM with n_g generations,

V_{CKM} is a $n_g \times n_g$ unitary matrix
 \downarrow
 n_g^2 parameters

However, $(2n_g - 1)$ phases can be removed by rephasing the $2n_g$ quark fields.

$$N_{\text{param.}} = n_g^2 - (2n_g - 1) = (n_g - 1)^2$$

$$N_{\text{angle}} = \frac{1}{2} n_g (n_g - 1)$$

$$N_{\text{phase}} = N_{\text{param.}} - N_{\text{angle}} = \frac{1}{2} (n_g - 1)(n_g - 2)$$

A little bit of history:

15a.

Kobayashi and Maskawa received the Nobel Prize for pointing out that in the SM for three generations (or more) the CKM matrix can lead to CP violation.

Question - why didn't Cabibbo receive the Nobel Prize?

In my opinion, the EPS Hep board took a better decision

Cabibbo - EPS prize

Kobayashi, Maskawa - EPS prize

Cabibbo universality - "unification" of:

- muon decay
- neutron decay
- strange particle decays.

Counting parameters in the Flavour sector of the SM:

- 3 up quark masses
 - 3 down quark masses
 - 3 mixing angles
 - 1 CP-violating phase
-
- 10 parameters

Similarly, in the leptonic sector with Majorana neutrinos one has:

$$10 + 2 \text{ Majorana phases} = 12 \text{ parameters}$$

Altogether:

$$10 + 12 = 22 \text{ parameters!}$$

just in the Flavour sector of the SM.

\Rightarrow The SM cannot be the final theory !!

Feynman's Suggestion

Do you want to be famous?

Do you want to be a King?

Do you want more than
a Nobel Prize?

Then solve the Mass Problem!

What is "the origin" of such large number of parameters?

Gauge invariance does not constrain the flavour structure of Yukawa couplings!

$Y_u, Y_d \rightarrow 3 \times 3$ arbitrary complex matrices

$$18 + 18 = 36 \text{ parameters!}$$

Large redundancy due to the freedom to make Weak-basis transformations which keep gauge currents invariant (diagonal, real) but can change drastically Y_u, Y_d

Start with Y_u, Y_d , written in a given Weak basis (WB). One is allowed to make the following WB transformations:

$$u_L \rightarrow u_L = W_L u'_L$$

$$d_L \rightarrow d_L = W_L d'_L$$

$$u_R \rightarrow u_R = W_R^u u'_R$$

$$d_R \rightarrow d_R = W_R^d d'_R$$

Under this basis transformation

$$Y_u \rightarrow Y'_u = W_L^+ Y_u W_R^u$$

$$Y_d \rightarrow Y'_d = W_L^+ Y_d W_R^d$$

Important point :

The allowed WB transformations depend on the gauge model that one is considering. For example in Left-Right symmetric models one has

$$W_R^u = W_R^d$$

By making use of the freedom to make WB transformations, one may :

- (i) Choose, without loss of generality, (WLG) a WB where Y_u (or M_u) is diagonal, real, while M_d is hermitian with only one rephasing invariant phase.
- (ii) Same as (i), with M_u, M_d interchanged
- (iii) Create "artificial" texture zeros in M_u , in M_d or in both. Of course these "zeros" have no physical meaning, they are just a choice of basis.

Example : The NNI basis

Starting from arbitrary Yukawa couplings Y_u , Y_d one can make WB transformations leading to the following for M_u , M_d

$$M_u \propto \begin{bmatrix} 0 & a_u & 0 \\ a'_u & 0 & b_u \\ 0 & b'_u & c_u \end{bmatrix}$$

$$M_d \propto \begin{bmatrix} 0 & a_d & 0 \\ a'_d & 0 & b_d \\ 0 & b'_d & c_d \end{bmatrix}$$

Of course, the NNI basis has no physical implications, for quark masses and mixing.

But NNI texture + hermiticity of M_u , M_d leads to the

Fritzsch Ansatz

CP Violation

The most natural Approach

How can one find out whether a given

Lagrangian violates CP or not?

- J.Bernabeu, M.Gronau,
GCB
- G.C.B., L.Lavoura and
J.Silva

The CP transformation properties of the fields of a given Lagrangian are dictated by the part of the Lagrangian which conserves CP.

The complete Lagrangian can be written:

$$\mathcal{L} = \mathcal{L}_{\text{CP}} + \mathcal{L}_{\text{remaining}}$$

\downarrow
CP conserving part

In order to analyse whether \mathcal{L} (the full Lagrangian) violates CP (or not) one has to check whether the CP transformation under which \mathcal{L}_{CP} is invariant, implies non-trivial restrictions on $\mathcal{L}_{\text{remaining}}$. \mathcal{L} leads to CP violation if and only if such restrictions exist and are not satisfied.

In the SM, \mathcal{L}_{CP} are the gauge interactions. The most general CP transformation of the quark fields which leaves the gauge interactions invariant is:

$$CP \ u_L^o (CP)^+ = K_L \gamma^o C \bar{u}_L^o {}^T$$

$$CP \ d_L^o (CP)^+ = K_L \gamma^o C \bar{d}_L^o {}^T$$

$$CP \ u_R^o (CP)^+ = K_R^u \gamma^o C \bar{u}_R^o {}^T$$

$$CP \ d_R^o (CP)^+ = K_R^d \gamma^o C \bar{d}_R^o {}^T$$

K_L, K_R^u, K_R^d being unitary matrices in flavour space
In order for the mass terms (or alternatively the Yukawa terms) to be CP invariant, the mass matrices have to satisfy the following constraint:

$$U_L^+ m_u U_R^u = m_u^*$$

$$U_L^+ m_d U_R^d = m_d^*$$

Important point: For another gauge group the CP transformations would be different.

Theorem - The Lagrangian of the SM is CP-invariant if and only if the quark mass matrices M_u, M_d are such that unitary matrices K_L, K_R^u, K_R^d exist, which satisfy previous equations.

Not of much practical use.

From previous equations, one obtains :

$$U_L^+ H_d U_L = H_d^* = H_d^T$$

$$U_L^+ H_u U_L = H_u^* = H_u^T$$

$$U_L^+ [H_u, H_d] U_L = \begin{bmatrix} H_u^T & H_d^T \end{bmatrix} = -[H_u, H_d]^T$$

↓

$$U_L^+ [H_u, H_d]^r U_L = -([H_u, H_d]^r)^T$$

r odd

↓

$$\text{tr} [H_u, H_d]^r = 0 \quad r \text{ odd}$$

We have not specified the number of generations !!

$$\text{tr} [H_u, H_d]^r = 0 \quad r \text{ odd}$$

For $r = 1$ trivially satisfied

For $r = 3$ it is automatically satisfied
for $n_g = 2$

For $n_g = 3$:

$$\begin{aligned} \text{tr} [H_u, H_d]^3 &= 6i (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \text{Im } Q \end{aligned}$$

In the SM, for 3 generations :

$$\text{tr} [H_u, H_d]^3 \neq 0 \iff \text{CP violation}$$

Comment : This method is completely general : it can be applied to any theory .

- Left-right symmetric theories
- SUSY extensions of the SM
- Leptonic Sector with Majorana Neutrinos
- Multi-Higgs Models
- CP violation relevant for Leptogenesis etc , etc .

This is specially useful in the presence of a Family Symmetry .

The presence of a family symmetry may "kill" CP violation in a theory which otherwise would have CP violation .

Exercises

1. Show that for arbitrary 2×2 hermitian matrices H_u, H_d , one has

$$\text{tr} [H_u, H_d]^3 = 0$$

2. Evaluate

$$\text{tr} [H_u, H_d]^3$$

For $n_g = 3$, in terms of quark masses and mixings

3. Consider a model, based on $SU(2) \times U(1) \times SU(3)_c$ with two generations of leptons, with Majorana neutrinos and derive a necessary and sufficient condition for CP violation, in terms of a weak-basis invariant

4. Study CP violation at Lagrangian level, in a general theory with 2 Higgs doublets

Some questions...

- Why is there "family replication?"
why 3?
- "Who ordered the moon?"
Rabi's question has been "amplified".
- How to understand the observed pattern of fermion masses and mixing?
- Why is leptonic mixing large in contrast to small quark mixing?

Attempts at Solving the Flavour Puzzle

- Introduce a Family Symmetry

$$SU(2)_L \times U(1) \times SU(3)_C \times S_F$$

$S_F \rightarrow$ family symmetry under which fermion families transform non-trivially

Questions:

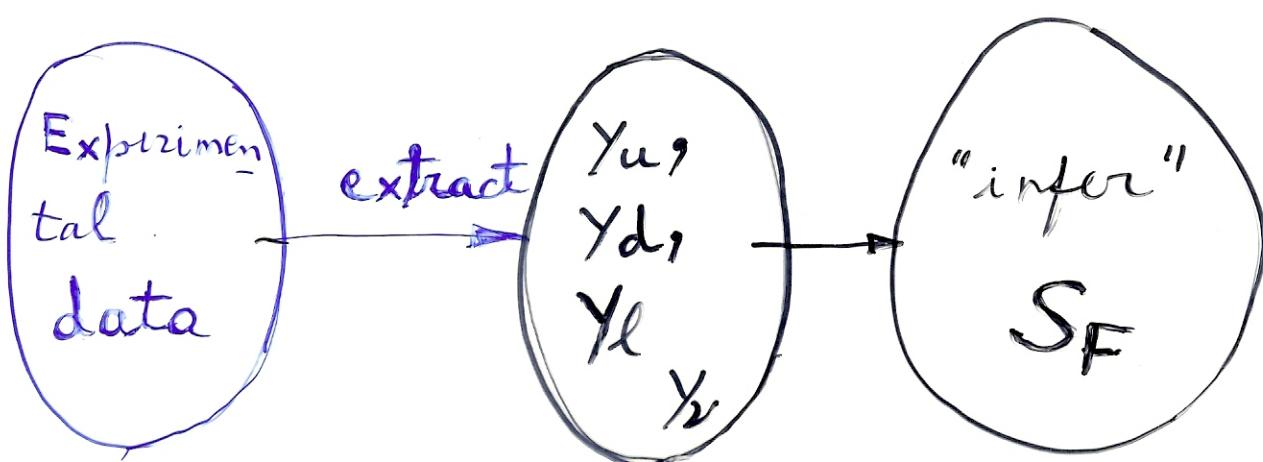
How to choose S_F ? Discrete, Continuous?

How to be "inspired" by experiment on the choice of S_F ?

- Postulate "texture zeros"?

Question :

Taking into account that there has been great progress in the last decade(s) in determining with some accuracy quark masses, charged lepton masses, neutrino mass differences, V_{CKM} , V_{PMNS} , why is it so difficult to use a bottom-up approach?



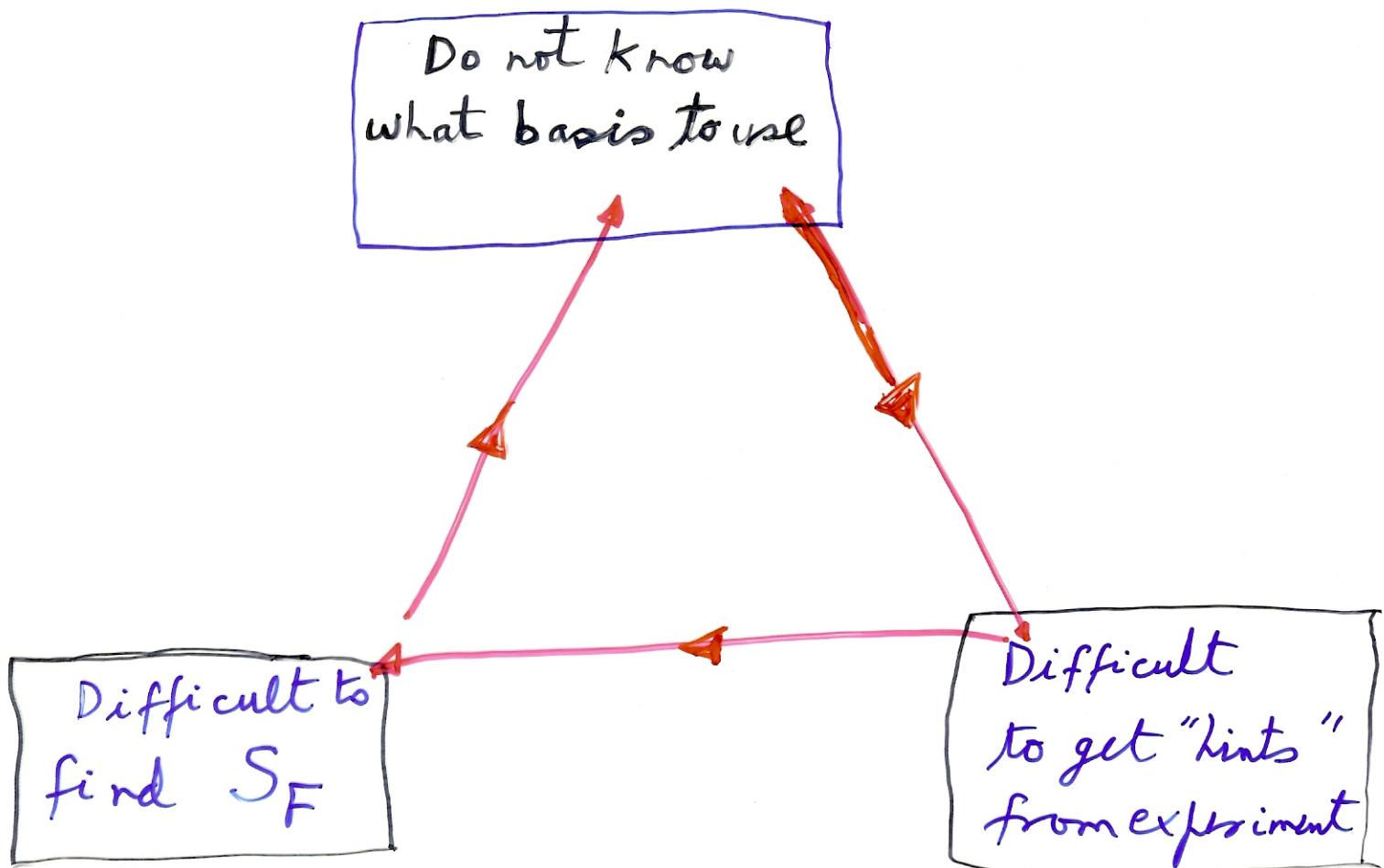
A possible answer :

There is large redundancy
in Y_u, Y_d, Y_l, Y_ν

Difficulty :

Even if Nature has chosen some
Family Symmetry S_F in what
Weak-basis will this symmetry
be apparent?

The Vicious Triangle



We need some bright idea!

Some early attempts

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One of first suggestions, in the context of gauge theories, was given by Weinberg :

$$M_u = \begin{bmatrix} 0 & au \\ * & au \end{bmatrix} ; \quad M_d = \begin{bmatrix} 0 & ad \\ * & ad \end{bmatrix}$$

Then one has :

$$\theta_c = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\varphi} \sqrt{\frac{m_u}{m_c}} \right|$$

The matrices M_u, M_d are assumed to be hermitian.

This idea was later generalized by Fritzsch for the case of 3 generations.

Fritzsch generalization to 3 generations

$$M_u = \begin{bmatrix} 0 & au & 0 \\ a_u^* & 0 & bu \\ 0 & b_u^* & cu \end{bmatrix}; M_d = \begin{bmatrix} 0 & ad & 0 \\ a_d^* & 0 & bd \\ 0 & b_d^* & cd \end{bmatrix}$$

The matrices M_u , M_d (or the corresponding Yukawa couplings) are assumed to be :

- Hermitian
- to have the above 3 texture zeros each.

Then, one recuperates the successfull prediction :

$$|V_{us}| = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\gamma_1} \sqrt{\frac{m_u/m_c}} \right|$$

but, unfortunately one also obtains :

$$|V_{cb}| = \left| \sqrt{\frac{m_s}{m_b}} - e^{i\gamma_2} \sqrt{\frac{m_c}{m_t}} \right|$$

When it was suggested, the Ansatz was viable, since the top quark had not been discovered. With the discovery of a quite heavy top (another surprise for theorists), the Ansatz is ruled out since it predicts a too large value for $|V_{cb}|$.

Experimental value : $|V_{cb}| \approx .04 \ll \sqrt{\frac{m_s}{m_b}}$

One would need a significant cancellation between the two terms contributing to $|V_{cb}|$. This is not possible with a heavy top.

More recently, P. Ramond, Roberts and

G.G. Ross

have classified all the "texture zero Ansätze consistent with experiment at the time, based on hermitian mass matrices.

Quite a few of these Ansätze are already ruled out by present more accurate knowledge of V_{CKM} .

A common feature of all the texture zero Ansätze classified by RRR

have a common feature :

A zero in the $(1,1)$ element :

$$M_u = \begin{bmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix}; \quad M_d = \begin{bmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix}$$

Why is the $(1,1)$ texture zero important?

Recall the diagonalization of quark mass matrices:

$$U^+ M_d U = \text{diag}(m_d, m_s, m_b)$$

$$M_d = U d U^+$$



$$(M_d)_{11} = m_d |U_{11}|^2 - m_s |U_{12}|^2 + m_b |U_{13}|^2 = 0$$

If the term $m_b |U_{13}|^2$ can be neglected,
one obtains

$$\frac{|U_{12}|}{|U_{11}|} \approx \sqrt{m_d/m_s}$$

Similarly for the up quark sector.

The successful formula for $|V_{us}|$
is retained.

Suppose that one discovers a "Theory of Flavour". How could one be sure that this is the right theory? How could one test this theory experimentally?

More specifically, let us consider that one has a Theory of Flavour for the quark and lepton sectors with N_p free parameters. Suppose that

$$N_p \ll 22$$

Suppose that this Theory fits all experimental data on fermion masses and mixing.

Would the author receive a nice call from Sweden?

How would one know that it is just a numerical coincidence?

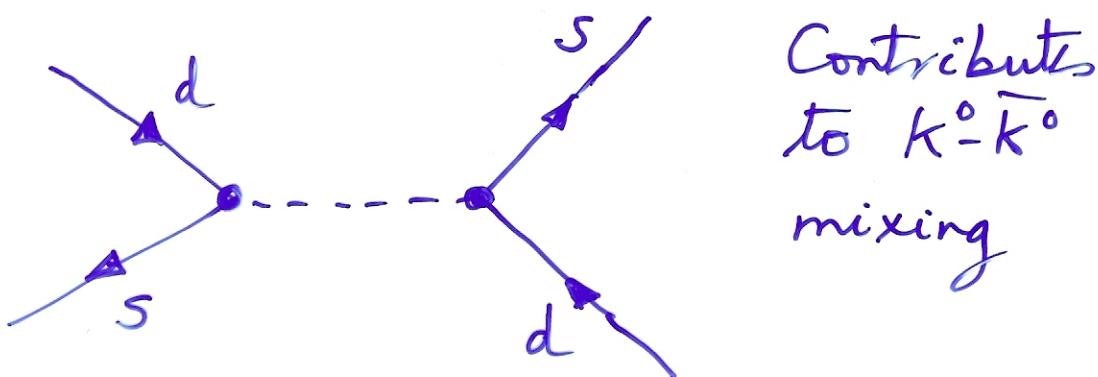
A sentence attributed to Landau:

"Give me 3 parameters and
I will fit any data"

An ideal "Theory of Flavour" should "hopefully" predict New Phenomena which can be tested experimentally

An example of New Phenomena which could be predicted by a "Theory of Flavour": FCNC mediated (for example) by Neutral Higgs

Of course, one should be aware of strict bounds on FCNC mediated by neutral Higgs.



But a theory of flavour should have its own natural mechanism for suppressing FCNC

Two important results

- Gatto et al have shown that if one imposes Natural Flavour Conservation (NFC) on a multi-Higgs theory through the so-called naturality groups, then it turns out that essentially the only possibility (realistic) is having only one Higgs giving mass to quarks of a given charge. But then mixing remains arbitrary!
- Existence proof of a Natural Suppression mechanism beyond NFC.

G.C. B, W. Grimus,
L.avoura

