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Standard KM model of CP violation and Flavor Physics

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On-going discussion (last 1.5 years) with Wai-Yee Keung

Being a theorist today ...

Some day you wake up and decide to ask

* Why is the KM model working so poorly?

---- take SUSY, $\tilde{b}$–$\tilde{s}$ mixing,

CP violation in ϕK_S (before summer 2002)

etc ... as Antonio ...

Some day you ask instead

* Why is KM model working so well?

---- Ignoring the annoying Belle data ...

Story: Some 20+ years ago ... Lincoln ...

"It is like: We already know the answer

We just have to figure out what the question

is ...."

Story: Some 5+ years ago ...

Fermilab ϵ'/ϵ exp. v.s CERN ϵ'/ϵ exp.

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Why is KM model working so well ?

to SUSY

or

NOT to SUSY

Make it SUSY in the afternoon

may be . . .

Why is KM model working so well?

Origin of flavor $\equiv$ origin of CP violation

$\longleftarrow$ Yukawa couplings

CP violation $\Leftarrow$ interference between charged currents

* Only when all three generations are involved $\longrightarrow$ have exactly ONE CP violating phase
* A beautiful & subtle theory of CPX

$\Rightarrow$ tight connection between CPX & flavor physics

$\Rightarrow$ explain why CPX so small in kaon systems

At kaon scale, heavy third generation almost decouples $\Rightarrow$ effective CPX is superweak-like even if KM phase can be of order one

* Any weakness in KM ?

① BAU : higher energy physics

new sources of CP violation

② Strong CP θ problem

two levels

ⓐ tree level

$$\theta = \theta_0 - \mathrm{Arg}(\det M^u M^d)$$

ⓑ loop level

Amazingly, by having tight connection between flavor & CP, KM model seems to have already solved its loop level problem

If Θ set to zero at tree level,

* finite loop correction will not occur until at 3-loop level (2 weak loop one strong loop)
  $\longrightarrow$ small
* log-div. correction appears first at 7-loop level (14th order in g_2), (and not obvious that they won't be cancelled either).
  $\longrightarrow$ small even if the cutoff $\Lambda \to M_{Pl}$

Lesson : $\Theta = 0$ point of KM is quite robust though not technically nature

* In some sense, strong CP problem in KM is only a tree level problem
* Solve strong CP problem in KM means to find a high energy theory that gives small Θ_{eff} as an effective tree coupling in KM

What is the high energy theory that can produce KM with small θ_{true} as an effective theory?

From flavor problem to θ problem

From θ problem to flavor problem *

Two examples: (out of many...)

two unpublished papers

Masiero + Yanagida hep-ph/9812225

Glashow hep-ph/0110178

good papers ...

Illustrate the goal and difficulty

① Without extra heavy fermions → Glashow

② With extra vectorial heavy fermions

→ Nelson + Barr → Masiero Yanagida

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* One can solve strong CP problem without touching the flavor issue.

— leave the tight connection between CP & flavor in KM alone.

Ex: use a parity mirror copy

$$SU(3) \times [SU(2) \times U(1)] \times [\widehat{SU}(2) \times \widehat{U}(1)]$$

$\rightarrow$ two sectors cancel their loop correction to θ

$\rightarrow$ very small θ

* Hope to use strong CP as a guide to find the correct flavor physics at high energy

$\rightarrow$ Any extension of KM model at high energy $\Rightarrow$ disturb the nice tight connection between CP & flavor in KM

$\Rightarrow$ new dangerous 1-loop contribution

Masiero-Yanagida : Hermitean Mass Matrix

$q_{Li} \equiv \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$, u_{Ri} d_{Ri} ; $U_{L,Ri}$, $D_{L,Ri}$ $\quad i=1 \cdots 3$

$\underline{\text{SU(2) singlets}}$

horizontal (Flavor) $SU(3)_F$ symmetry : all triplets

Usual Higgs : H

break $SU(3)_F$ & give heavy fermion mass :

$\underbrace{\text{3 Octets}}$ $\phi^{a=1\cdots 8}_{\alpha=1\cdots 3}$ One singlet Φ

$\hookrightarrow$ to break $SU(3)_F$ completely

Yukawa : $\bar{d}_R \left(g_{d\alpha} (\phi^a_\alpha \lambda^a) + g'_d \Phi \right) D_L$

$+ h_d \bar{D}_R H^\dagger q_L + h.c.$

$+$ Similar terms for up-quarks

* Impose a discrete symmetry to kill $\bar{d}_R d_L$ term

* Impose CP : kill tree level θ (high energy)

$\longrightarrow$ real couplings

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Mass matrix

$$\begin{array}{c|cc} & d_L & D_L \\ \hline d_R & 0 & g_d\langle\phi^a\rangle\lambda^a + g_d'\langle\Phi\rangle \\ D_R & h_d\langle H^+\rangle \mathbb{I} & M_D\,\mathbb{I} \end{array}$$

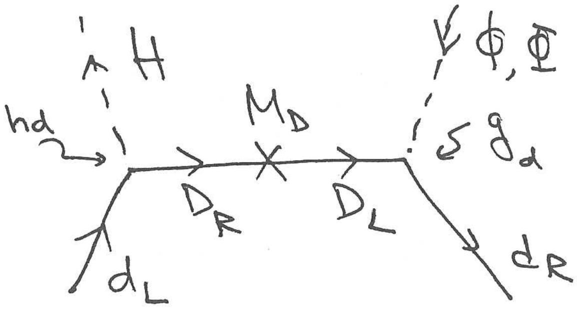
→ P is broken in SM already, ⇒ need C violation

→ In any Lie group, once C is defined as

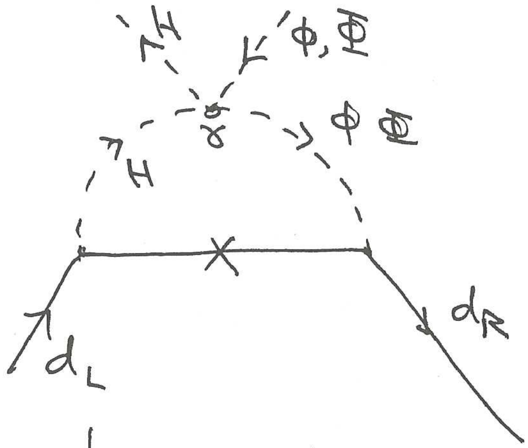
$\text{irrep} \xrightarrow{C} \text{conjugate irrep}$

→ not all components of adj can have the same C property

* One loop θ



low energy quark mass matrix



loop correction to θ

→ one loop correction must be suppressed by assuming the quartic coupling γ is small

→ One can use this as the starting framework to explore flavor texture etc ...

General mass matrix with loop corrections

	d_L	D_L
d_R	$H^{2n+1}\phi^{2n+1}$	$H^{2n}\phi^{2n+1}$
D_R	$H^{2n+1}\phi^{2n}$	$H^{2n}\phi^{2n}$

$SO(3)_F$ flavor model

$q_L \quad u_R \quad d_R \qquad U_{L,R} \qquad D_{LR}$

all $SO(3)$ vectors (triplets)

Usual Higgs : H

extra $SO(3)$ breaking scalar $\begin{cases} \text{symmetric } (\phi_S)_{ij} \\ \text{antisymmetric } (\phi_A)_{ij} \end{cases}$

* Mass matrix

$$M_d \sim \begin{array}{c c} & \begin{array}{cc} d_R & D_R \end{array} \\ \begin{array}{c} d_L \\ D_L \end{array} & \begin{bmatrix} h_d \langle H^+ \rangle \mathbb{1} & \mu_d + g_d^S \langle \phi_S \rangle + i g_d^A \langle \phi_A \rangle \\ h_d' \langle H^+ \rangle \mathbb{1} & \mu_D + g_D^S \langle \phi_S \rangle + i g_D^A \langle \phi_A \rangle \end{bmatrix} \end{array}$$

* CP symmetry $\quad \phi_S \to \phi_S \qquad$ both real

$\phi_A \to -\phi_A$

$\langle \phi_S \rangle, \langle \phi_A \rangle$ real & break CP

* One loop θ : similar to Masiero-Yanagida

At 1-loop

$$M_d \sim \begin{bmatrix} a\mathbb{1} + h_{11} & H_{12} \\ b\mathbb{1} + h_{21} & H_{22} \end{bmatrix}$$

Extra discrete symmetry to suppress one-loop Θ

Z_2: $u_R, d_R, \phi_A, \phi_S \to -(u_R, d_R, \phi_A, \phi_S)$

$\Rightarrow h_d = g_{DS} = g_D^A = 0$

$$M_d \sim \begin{bmatrix} 0 & \mu_A \mathbb{I} + g_d^S \langle \phi_S \rangle + g_d^A \langle \phi_A \rangle \\ h_d' \langle H^+ \rangle \mathbb{I} & \mu_D \mathbb{I} \end{bmatrix}$$

at tree level

~~At~~ One-loop "0" $\longrightarrow$ small hermitean h

$$M_d \sim \begin{bmatrix} h & H \\ b\mathbb{I} & \mu_D \mathbb{I} \end{bmatrix} \to \det M_d = \overbrace{|h\mu_D - bH|}^{\det} \Rightarrow \text{real}$$

$\longrightarrow$ other one loop correction also give real det.

$\Rightarrow \Theta$ receives contribution only at two loop

* proceed to play with potential $SO(3)_F$ texture

Conclusion

KM is beautiful and working and for some reason θ_{tree} is small.

The answer should lie in the flavor physics of high energy model.

* CP X from relative phases between H_i

$\epsilon_{12}, \epsilon_{23}, \epsilon_{21}, \epsilon_{32}$ have the same phase

$\epsilon_{13}, \epsilon_{31}$ same phase

* One can adjust quark phase convention such that

$$\epsilon_{12} \quad \epsilon_{23} \quad \epsilon_{21} \quad \epsilon_{32} \quad \text{are real}$$

$\Rightarrow$ phase of $\epsilon_{13}, \epsilon_{32} \longrightarrow$ KM phase

*
$$V_{12} \cong \frac{\epsilon_{12}}{m_s}$$

$$V_{23} \cong \frac{\epsilon_{23}}{m_b}$$

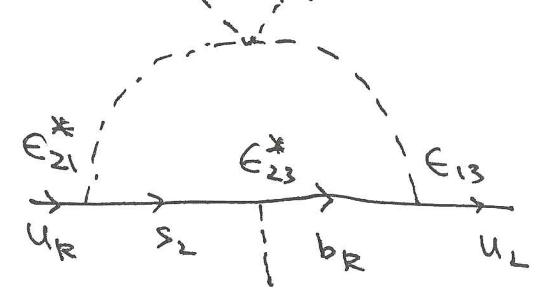
$$V_{13} \cong \frac{\epsilon_{13}}{m_b}$$

contribution from diagonalization of up quark mass negligible

$\epsilon_{23} \sim 450$ MeV

$\rightarrow$ fit data : $\epsilon_{12} \sim 25$ MeV $\quad \epsilon_{13} \sim 13$ MeV

* One loop $\bar{\theta}$: correction to up quark mass



$$\Delta\bar{\theta} = \left(\frac{1}{4\pi}\right)^2 \frac{\epsilon_{13}\epsilon_{23}^*\epsilon_{21}}{v_2 m_u} K$$

$$\sim 10^{-9}$$

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Glashow model : with triangular mass matrix

$SU(2)_L \times U(1) \times U(1)_F$

3 doublets $H_0(0)$, $H_1(1)$, $H_2(\overset{F}{2})$

$u(+1)$ $c(0)$ $t(-1)$

similarly for other quark flavors

Quark mass matrix

$$\hat{M}_d \sim \begin{array}{c} \\ d_L \\ s_L \\ b_L \end{array} \begin{array}{c} \begin{array}{ccc} d_R & s_R & b_R \end{array} \\ \begin{bmatrix} y_{d_{11}}\langle H_0\rangle & y_{d_{12}}\langle H_1\rangle & y_{d_{13}}\langle H_2\rangle \\ 0 & y_{d_{22}}\langle H_0\rangle & y_{d_{23}}\langle H_1\rangle \\ 0 & 0 & y_{d_{33}}\langle H_0\rangle \end{bmatrix} \end{array}$$

$$\hat{M}_u \sim \begin{array}{c} u_L \\ c_L \\ t_L \end{array} \begin{bmatrix} y_{u_{11}}\langle H_0^*\rangle & 0 & 0 \\ y_{u_{12}}\langle H_1^*\rangle & y_{u_{22}}\langle H_0^*\rangle & 0 \\ y_{u_{13}}\langle H_2^*\rangle & y_{u_{23}}\langle H_1^*\rangle & y_{u_{33}}\langle H_0^*\rangle \end{bmatrix}$$

$$\hat{M}_d \sim \begin{bmatrix} m_{d0} & \epsilon_{12} & \epsilon_{13} \\ 0 & m_{s0} & \epsilon_{23} \\ 0 & 0 & m_{b0} \end{bmatrix} \qquad \hat{M}_u \sim \begin{bmatrix} m_{u0} & 0 & 0 \\ \epsilon_{21}^* & m_{c0} & 0 \\ \epsilon_{31}^* & \epsilon_{32}^* & m_{t0} \end{bmatrix}$$

* One can also make $\hat{M}_d$ lower triangular & $\hat{M}_u$ upper

* Such structure can also be implemented by discrete symmetry instead of $U(1)_F$