A Common Origin for all CP violations

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SCALARS 2011, Poland

Warsaw, the 27th of August 2011

Works done with

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CP violation plays central rôle in Particle Physics and Cosmology

SM: Complex Cabibbo - Kobayashi - Maskawa matrix. Explicit CP violation
Complex Yukawa couplings

Experimental evidence for complex CKM

It is not possible to generate observed size of BAU in SM due in particular to smallness of CP violation in the SM

Phenomenological aspects of CP violation

(i) Quark sector, already discovered

Kaon sector, almost five decades ago

Christenson, Cronin, Fitch and Turlay (1964)

B sector, BaBar and Belle (2001)

(ii) Leptonic sector, expected

Any extension of SM accounting for ν masses and leptonic mixing leads in principle to CP violation

(iii) Generation of BAU, indirect evidence   Sakharov (1967)

new sources of CP violation beyond KM mechanism are required, Leptogenesis is a promising scenario

(iv) Strong CP problem

We put forward the conjecture that

all CP violating phenomena may
have a common origin

with CP spontaneously broken
at a high energy scale
through the phase of vev of complex scalar singlet

This single phase is at the origin of

- both low energy CP violation in quark and leptonic sectors
- strong CP problem solved via Nelson - Barr mechanism   Bento, Branco, Parada (91)
- possibility of having leptogenesis

Minimal scenarios for spontaneous $\cancel{CP}$

- two scalar doublets, ϕ_1, ϕ_2

T. D. Lee, 1974

- one scalar doublet (ϕ) and one scalar singlet (S)

Models with more than one scalar doublet have potentially large scalar mediated FCNC

In our case there will be ZFCNC, which are suppressed by $v/V = |\langle\phi\rangle| / |\langle S\rangle|$

δ_{KM} is generated, only effect left when $V \to \infty$

deviations of unitarity of V_{CKM} also suppressed by v/V

The model

SM fields + scalar singlet field (S)

One singlet charge-$\frac{1}{3}$ vectorial quark D^0 (D^0_L, D^0_R)

Three righthanded neutrino fields ν^0_R (one per generation)

Impose Z_4 symmetry under which

$$D^0 \rightarrow -D^0 \qquad S \rightarrow -S$$

$$\psi^0_\ell \rightarrow i\psi^0_\ell, \quad e^0_R \rightarrow i e^0_R, \quad \nu^0_R \rightarrow i\nu^0_R$$

ψ^0_ℓ are the lefthanded lepton doublets
all other fields remain invariant under Z_4

CP invariance is imposed on the Lagrangian

In hadronic + scalar sector the discrete symmetry is Z_2

Bento, Branco, Parada (91)

The scalar sector

Most general $SU(2)\times U(1)\times Z_4$ invariant potential

$$V = V_0(\phi, S) + \left(\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^\dagger \phi\right)\left(S^2 + S^{*2}\right) + \lambda_3\left(S^4 + S^{*4}\right)$$

V_0 contains only terms with no phase dependence

after spontaneous CP violation

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \qquad \langle S \rangle = \frac{V e^{i\alpha}}{\sqrt{2}}$$

for range of parameters of the potential

Bento, Branco (90)

V can be much larger than EW scale
α is the only source of CP violation
CP violation generated at high energy scale

Hadronic sector

non-trivial phase at low energies in CKM requires at least one singlet vectorial quark

D^0 and ν_R's establish connection between $\cancel{CP}$ at high and low energies

Yukawa terms (quarks)

$$\mathcal{L}_q = \bar{\psi}_q^0 G_u \phi u_R^0 + \bar{\psi}_q^0 G_d \tilde{\phi} d_R^0 + (f_q S + f_q' S^*) \bar{D}_L^0 d_R^0 + \tilde{M} \bar{D}_L^0 D_R^0 + h.c.$$

$D \to -D \qquad S \to -S$

all couplings are real

$$M_D = \frac{V}{\sqrt{2}} \left(f_+^q \cos\alpha + i f_-^q \sin\alpha \right)$$

$$f^\pm = f_q \pm f_q'$$

$$\mathcal{M}_d = \left(\begin{array}{c|c} m_d^0 = \frac{v}{2} G_d & 0 \\ \text{real} & 0 \\ & 0 \\ \hline M_D & \tilde{M} \\ & \text{real} \end{array} \right)$$

no $\bar{d}_L^0, D_R^0$ coupling

$M_D, \tilde{M} \gg$ EW scale

Hadronic sector (cont)

Nelson - Barr criteria for strong CP

$$\bar{\theta} = \theta_{QCD} + \theta_{QFD}$$

CP conserved at the Lagrangian : $\theta_{QCD} = 0$

$\theta_{QFD} = \arg(\det m) = 0$ at tree level

m denoting the quark mass matrices

recall

$$\mathcal{M}_d = \left(\begin{array}{c|c} \underset{\text{real}}{m_d^0} & \begin{matrix}0\\0\\0\end{matrix} \\ \hline M_D & \underset{\text{real}}{\tilde{M}} \end{array}\right), \qquad M_u \text{ real}$$

higher order corrections to $\bar{\theta}$ are finite and calculable

Hadronic sector (cont.)

choose WB where M_u is diagonal

$$U_L^\dagger \mathcal{M}_d U_R = \begin{pmatrix} d & 0 \\ 0 & \bar{M} \end{pmatrix} \qquad d = \mathrm{diag}(m_d, m_s, m_b)$$

$\bar{M}$ heavy quark mass

$$\mathcal{M}_d = \left(\begin{array}{c|c} m_d^0 & \begin{matrix} 0 \\ 0 \\ 0 \end{matrix} \\ \hline M_D & \tilde{M} \end{array}\right) , \qquad U_L^\dagger \mathcal{M}_d \mathcal{M}_d^\dagger U_L = \begin{pmatrix} d^2 & 0 \\ 0 & \bar{M}^2 \end{pmatrix}$$

$$U_L = \begin{pmatrix} K & R \\ S & T \end{pmatrix}$$

limit $M_D, \bar{M} \gg O(m_d)$

$$\bar{M}^2 \simeq \left(M_D M_D^\dagger + \tilde{M}^2 \right) \equiv M^2$$

$$K \equiv V_{CKM}$$

$$K^{-1} m_{eff} m_{eff}^\dagger K = d^2$$

$$m_{eff} m_{eff}^\dagger = \underbrace{m_d^0 m_d^{0\dagger}}_{\text{real}} - \underbrace{\frac{m_d^0 M_D^\dagger M_D m_d^{0\dagger}}{M_D^\dagger M_D + \tilde{M}^2}}_{\text{complex}}$$

if $|M_D|, |\tilde{M}|$ are of same order of magnitude the phase α from $\langle S \rangle$ generates non-trivial CKM

Hadronic sector (cont.)

$$S \simeq - \frac{M_D \, m_d^{0\dagger} V_{CKM}}{M^2} \left(1 + \frac{\overline{m}^2}{M^2}\right) \sim \mathcal{O}\left(\frac{v}{V}\right)$$

$M^2 = M_D M_D^\dagger + \tilde{M}^2 \simeq \overline{M^2}$ heavy quark mass^2 $\qquad U = \begin{pmatrix} K & R \\ S & T \end{pmatrix}$

For very large V $\quad$ ($V \sim M_{GUT} \sim 10^{15}$ GeV)

δ_{KM} is the only leftover effect at low energies

Experimental evidence for complex CKM

For not so large V $\quad$ (e.g. V order a few TeV)

V_{CKM} (K) deviations from unitarity $\quad (K^\dagger K + S^\dagger S = \mathbb{1})$

ZFCNC in the down quark sector

new contributions to $B_d - \overline{B_d}$ and $B_s - \overline{B_s}$ mixing

Both effects are closely related

Hadronic sector (cont.)

Naturally small deviations from 3x3 unitarity of V_{CKM}

Naturally small Z FCNC

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t})_L \gamma^\mu \underbrace{[K, R]}_{(V_{CKM})_{3\times 3}} \begin{bmatrix} d \\ s \\ b \\ D \end{bmatrix}_L W_\mu^+$$

$$\mathcal{L}_Z = -\frac{g}{2\cos\theta_W} \Big\{ (\bar{u}, \bar{c}, \bar{t})_L \gamma^\mu \begin{bmatrix} u \\ c \\ t \end{bmatrix}_L - \left[\bar{d}\,\bar{s}\,\bar{b}\,\bar{D}\right]_L \begin{bmatrix} K^\dagger K & K^\dagger R \\ R^\dagger K & R^\dagger R \end{bmatrix} \gamma^\mu \begin{bmatrix} d \\ s \\ b \\ D \end{bmatrix}_L - \sin^2\theta_W J^\mu_{em} \Big\} Z_\mu$$

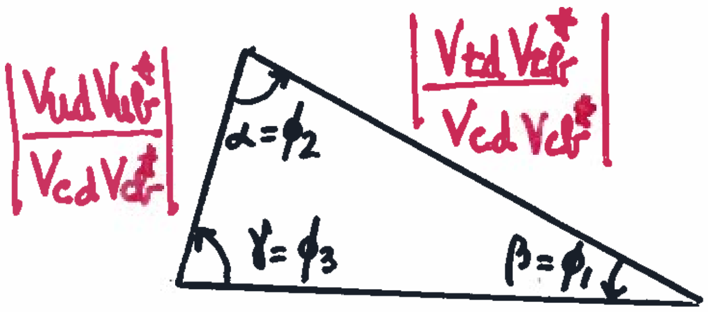
$$U_L \equiv \begin{pmatrix} K & R \\ S & T \end{pmatrix} \qquad S \sim \mathcal{O}\left(\frac{m}{M}\right)$$

$$K^\dagger K + S^\dagger S = \mathbb{I}$$

$$K^\dagger K = \mathbb{I} - \mathcal{O}\left(\frac{m^2}{M^2}\right)$$

Hadronic sector (cont)

New Physics contributions to $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing



- affects the extraction of $|V_{td}|$, $|V_{ts}|$ from data
- affects the measurement of angles of the unitarity triangle

$$S_{J/\psi K_S} = \sin(2\beta + 2\theta_d) = \sin(2\tilde{\beta})$$

$$S_{\rho^+\rho^-} = \sin(2\alpha - 2\theta_d) = \sin(2\tilde{\alpha})$$

How to detect the presence of new physics?

Hadronic sector (cont.)

Use exact relations predicted by unitarity

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & \cdots \\ V_{cd} & V_{cs} & V_{cb} & \\ V_{td} & V_{ts} & V_{tb} & \\ \vdots & & & \ddots \end{pmatrix}$$

Freedom to rephase quarks

$\downarrow$

Only four independent rephasing invariant phases in 3×3 sector of CKM matrix of arbitrary size irrespective of number of generations, even for non unitary CKM

Nine moduli in 3×3 block

Useful phase convention

$$\arg(V_{CKM}) = \begin{pmatrix} 0 & \chi' & -\gamma \\ \pi & 0 & 0 \\ -\beta & \pi+\chi & 0 \end{pmatrix}$$

Possible to reconstruct full V_{CKM} in the SM with $\gamma, \beta, \chi, \chi'$ Aleksan, Kayser, London (1994,

definitions

$\gamma \equiv \arg(-V_{ud} V_{cb} V_{ub}^{*} V_{cd}^{*})$; $\beta_s \equiv \chi \equiv \arg(-V_{cb} V_{ts} V_{cs}^{*} V_{tb}^{*})$

$\beta \equiv \arg(-V_{cd} V_{tb} V_{cb}^{*} V_{td}^{*})$; $\beta_K \equiv \chi' \equiv \arg(-V_{us} V_{cd} V_{ud}^{*} V_{cs}^{*})$

Exact relations from orthogonality of rows and of columns

Botella, Branco, Nebot, MNR (2003)

Examples

(sb) $$\frac{\sin\chi}{\sin(\gamma+\chi')} = \frac{|V_{us}|\,|V_{ub}|}{|V_{ts}|\,|V_{tb}|}$$

(db) $$|V_{ub}| = \frac{|V_{cd}||V_{cb}|}{|V_{ud}|}\,\frac{\sin\beta}{\sin(\gamma+\beta)} \longrightarrow \text{extraction of } \theta_d$$

(sb) $$\sin\chi = \frac{|V_{us}|\,|V_{ub}|}{|V_{cs}|\,|V_{cb}|}\,\sin(-\chi+\chi'+\gamma) \longrightarrow \text{extraction of } \theta_s$$

From first two

$$\sin\chi = \frac{|V_{us}||V_{cd}||V_{cb}|}{|V_{ts}||V_{tb}||V_{ud}|}\,\frac{\sin\beta\,\sin(\gamma+\chi')}{\sin(\gamma+\beta)}$$

can be simplified to

$$\sin\chi \simeq \frac{|V_{us}|^2}{|V_{ud}|^2}\,\frac{\sin\beta\,\sin\gamma}{\sin(\gamma+\beta)}$$

Aleksan, Kayser, London (1994)

Silva and Wolfenstein (1997)

Leptonic sector

$S \to -S \qquad \Psi_\ell^0 \to i\Psi_\ell^0 \qquad e_R^0 \to i e_R^0 \qquad \nu_R^0 \to i\nu_R^0$

Yukawa terms (leptons)

$$\mathcal{L}_\ell = \overline{\Psi_L^0}\, G_\ell\, \phi\, e_R^0 + \overline{\Psi_L^0}\, G_\nu\, \tilde{\phi}\, \nu_R^0 + \frac{1}{2}\nu_R^{0T} C \left(f_\nu S + f_\nu' S^*\right)\nu_R + h.c.$$

Z_4 no $\frac{1}{2}\nu_R^{0T} C \bar{M} \nu_R^0$ bare

a term of this form is generated through the couplings of ν_R^0 to the scalar singlet after Z_4 breaking

$$\mathcal{L}_m = -\left[\overline{\nu_L^0}\, m\, \nu_R^0 + \frac{1}{2}\nu_R^{0T} C M \nu_R^0 + \overline{\ell_L^0}\, m_\ell\, \ell_R^0\right] + h.c. =$$

$$= -\left[\frac{1}{2} n_L^T C \mathcal{M}^* n_L + \overline{\ell_L^0}\, m_\ell\, \ell_R^0\right] + h.c.$$

$$\mathcal{M} = \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \qquad m_\ell = \frac{v}{\sqrt{2}} G_\ell \quad \text{real}$$

$$m \equiv \frac{v}{\sqrt{2}} G_\nu \quad \text{real}$$

$$M = \frac{V}{\sqrt{2}}\left(f_\nu^+ \cos(\alpha) + i f_\nu^- \sin(\alpha)\right) \qquad f_\pm^\nu \equiv f_\nu \pm f_\nu'$$

Leptonic sector (cont.)

In WB where m_ℓ is chosen to be diagonal and real

V_{PMNS} $\quad -K^\dagger m \frac{1}{M} m^T K^* = d\nu$ $\quad$ complex

heavy neutrino masses, very approximately eigenvalues of M

In WB where m_ℓ and M diagonal and real

Unflavoured leptogenesis $\propto \sum_{k \neq j} \mathrm{Im}\,(m^\dagger m)_{jk} (m^\dagger m)_{jk}$

$N^k \to \ell_L^\pm \phi^\mp$, with $m = O^T d\, T$ $\quad (\bar{\nu}_L^0\, m\, \nu_R^0)$

O: orthogonal real $\quad$ T: unitary

$m^\dagger m = T^\dagger d^2 T$ entirely general $\Rightarrow$ leptogenesis is possible

Real T implies no $\cancel{CP}$ at low and high energies

$m m^\dagger$ is always real $\qquad$ $Br\,(\ell_i \to \ell_j \gamma)$ SUSY

Conclusions

One extra singlet scalar plus vectorial quarks provide interesting NP scenario with

Spontaneous CP violation

Naturally small violation of unitarity of V_{CKM}

related to

Naturally small ZFCNC

A common origin for all CP violations

Simple solution to the strong CP problem

Observable effects in B physics