Natural Alignment of Quark Flavors and Radiatively Induced Quark Mixings

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Based on arxiv 1804.01598[hep-ph], Abhish Dev, Rabindra N Mohapatra

What is flavor alignment?!

Flavor — Yukawa mass terms

$$-\mathcal{L} = \bar{Q}_i D_\mu \gamma^\mu Q_i + h_{ij}\bar{Q}_{Li}\phi u_{Rj} + \tilde{h}_{ij}\bar{Q}_{Li}\tilde{\phi} d_{Rj}$$

-

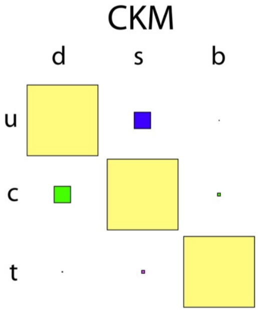
$$\begin{aligned} U_u^\dagger\{m_u, m_c, m_t\}U_u &= h_{ij}v_{ew} \quad U_{CKM} = U_u^\dagger U_d \\ U_d^\dagger\{m_d, m_s, m_b\}U_d &= \tilde{h}_{ij}v_{ew} \end{aligned}$$

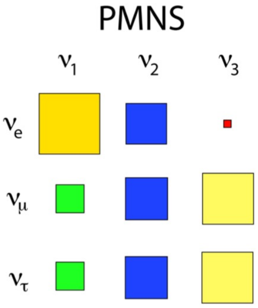
- U_{CKM} is totally arbitrary but...

What is flavor alignment?!

Flavor → $\bar{Q}_i D_\mu \gamma^\mu Q_i$; Yukawa mass terms → $h_{ij}\bar{Q}_{Li}\phi u_{Rj} + \tilde{h}_{ij}\bar{Q}_{Li}\tilde{\phi} d_{Rj}$

$$-\mathcal{L} = \bar{Q}_i D_\mu \gamma^\mu Q_i + h_{ij}\bar{Q}_{Li}\phi u_{Rj} + \tilde{h}_{ij}\bar{Q}_{Li}\tilde{\phi} d_{Rj}$$





Parity restored: Minimal Left-Right Model

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow \quad \Delta_R\ (\underline{1}, \underline{1}, \underline{3}, \underline{2})$$

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

$$\downarrow \quad \phi\ (\underline{1}, \underline{2}, \underline{2}, \underline{0})$$

$$SU(3)_C \times U(1)_Q$$

$$\Delta_L\ (\underline{1}, \underline{3}, \underline{1}, \underline{2})$$

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$$SU(3)_C \times U(1)_Q$$

$$\Delta_L\ (\underline{1}, \underline{3}, \underline{1}, 2)$$

MLRSM

J.C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566, (1975); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975); G. Senjanović and R. N. Mohapatra, Phys. Rev. D **12** 1502 (1975).

$$Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i (\underline{3}, \underline{2}, \underline{1}, \frac{1}{3}) \qquad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i (\underline{3}, \underline{1}, \underline{2}, \frac{1}{3})$$

$$\psi_{L,i} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i (\underline{1}, \underline{2}, \underline{1}, -1) \qquad \psi_{R,i} = \begin{pmatrix} N_R \\ e_R \end{pmatrix}_i (\underline{1}, \underline{1}, \underline{2}, -1)$$

Flavor alignment in the MLRSM model

$$\mathcal{L}_{Q,yukawa} = h_q \bar{Q}_L \phi Q_R + \tilde{h}_q \bar{Q}_L \tilde{\phi} Q_R$$

$$\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \qquad \kappa^2 + \kappa'^2 = v_{ew}^2 \qquad \tilde{\phi} = \tau_2 \phi^* \tau_2$$

-

$$M_u = h_q \kappa + \tilde{h}_q \kappa'$$
$$M_d = h_q \kappa' + \tilde{h}_q \kappa$$

- U^L_{CKM} and U^R_{CKM}

Flavor alignment in the MLRSM model

not necessary for down quark mass

$$\mathcal{L}_{Q,yukawa} = h_q \bar{Q}_L \phi Q_R + \tilde{h}_q \bar{Q}_L \tilde{\phi} Q_R$$

$$\langle\phi\rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \qquad \kappa^2 + \kappa'^2 = v_{ew}^2 \qquad \tilde{\phi} = \tau_2 \phi^* \tau_2$$

-

$$M_u = h_q \kappa + \tilde{h}_q \kappa'$$
$$M_d = h_q \kappa' + \tilde{h}_q \kappa$$

- $U^L_{CKM} = U^R_{CKM} = I$ $\qquad \kappa' < \kappa$
- Use your favorite symmetry

MLRSM $\times U(1)_{PQ}$

- Solves the strong CP problem; invisible axion dark matter

Q_L	+1	Q_R	-1
ψ_L	-2	ψ_R	-1
ϕ	+2	$\tilde{\phi}$	-2
Δ_L	+4	Δ_R	0
σ_1	+1	σ_2	$+2$

- forbids the $\tilde{h}_q \bar{Q}_L \tilde{\phi} Q_R$ term
- MLRSM$\times U(1)_{PQ} \xrightarrow{\langle \sigma_1 \rangle = v_{PQ}}$MLRSM
- $v_{PQ} \sim 10^{12}$ GeV for invisible axion

U(1)PQ

R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).

Higgs Potential

$$V(\phi, \Delta, \sigma) = V_0(\phi) + V_0(\Delta) + V_0(\sigma_2) + V_0(\sigma_1) + \sum_{\alpha,\beta} V_{\alpha,\beta}$$
$$+ \beta \mathrm{Tr} \phi^\dagger \tilde{\phi} \sigma_2 \sigma_2 + \mu_\sigma \sigma_2 \sigma_1^{*2} + \gamma Tr(\phi^\dagger \Delta_R^\dagger \tilde{\phi} \Delta_L)$$
$$+ L \leftrightarrow R.$$

$$V_{\alpha,\beta} = \lambda_{\alpha\beta}(H_\alpha^\dagger H)(H_\beta^\dagger H_\beta)$$

$$V_0(H) = -\mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

- L-R symmetry defined as $L \leftrightarrow R, \phi \to \phi^\dagger, \sigma_{1,2} \to \sigma_{1,2}^*$ which makes all couplings real
- need $\beta \mathrm{Tr} \phi^\dagger \tilde{\phi} \sigma_2 \sigma_2$ term to generate non-zero κ'
- Effective $h_q \bar{Q}_L \tilde{\phi} Q_R$ term is generated at tree from β term but can be absorbed by redefining h_q

Minimizing conditions

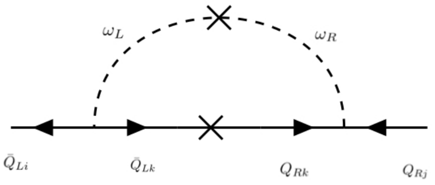
- Minimization gives

$$\kappa' \sim \frac{\beta v_2^2 \kappa}{M_\phi^2} \text{ and } v_2 \sim \frac{\mu_\sigma v_{PQ}^2}{M_{\sigma_2}^2}$$

- Discrete symmetry μ_σ is technically natural
- axion field:

$$a = \mathcal{N}\left(\frac{4\kappa'^2}{\kappa v_{PQ}}\chi_{\phi_1} + \frac{4\kappa'}{v_{PQ}}\chi_{\phi_2} - \frac{2v_2}{v_{PQ}}\chi_{\sigma_2} + \chi_{\sigma_1}\right)$$

Radiative mixings from color triplets



Radiative mixing via colored scalars

B. S. Balakrishna, Phys. Rev. Lett. **60**, 1602 (1988); B. S. Balakrishna, A. L. Kagan and R. N. Mohapatra, Phys. Lett. B **205**, 345 (1988); K. S. Babu, B. S. Balakrishna and R. N. Mohapatra, Phys. Lett. B **237**, 221 (1990).

- various options: color triplets

$\omega_L \quad (\underline{3}, \underline{1}, \underline{1}, -\frac{2}{3}, PQ = (-2 \quad))$

$$\mathcal{L}_Y = g_{ab}[Q_L^T \tau_2 \omega_L C^{-1} Q_L + L \to R]$$

- In the limit $m_{1,2} > m_{top}$,

$$M_{ij}^u = h_q \kappa + \frac{3 \sin 2\alpha}{16\pi^2} \ln \frac{m_1}{m_2} (g^\dagger h_q g)_{ij} \kappa', \qquad (1)$$

$$M_{ij}^d = h_q \kappa' + \frac{3 \sin 2\alpha}{16\pi^2} \ln \frac{m_1}{m_2} (g^\dagger h_q g)_{ij} \kappa.$$

Quark mass fit

Parameters	Mixing
$h_q = diag\{1.2651 \times 10^{-5},\ 7.3606 \times 10^{-3},\ 0.9954\}$, $\kappa/\kappa' = 41.1 \quad \kappa = 174.5\ GeV$	$J_{CP} = 2.64 \times 10^{-5}$
$g = \begin{pmatrix} 0.4642 & 0.5187 - 0.0008i & 0.0032 - 0.0338i \\ 0.5187 - 0.0008i & 0.7255 & 0.1079 - 0.0628i \\ 0.0032 - 0.0338i & 0.1079 - 0.0628i & 0.4005 \end{pmatrix}$	$\lvert V_{CKM} \rvert = \begin{pmatrix} 0.9747 & 0.2233 & 0.0034 \\ 0.2231 & 0.9741 & 0.0366 \\ 0.0095 & 0.0356 & 0.9993 \end{pmatrix}$

Masses

$$
\begin{aligned}
m_u &= 2.45\ MeV \\
m_d &= 5.57\ MeV \\
m_c &= 1.282\ GeV \\
m_s &= 93.68\ MeV \\
m_t &= 173.11\ GeV \\
m_b &= 4.75\ GeV
\end{aligned}
$$

Lepton masses

$$-\mathcal{L}_{L,yukawa} = h_\ell \bar{\psi}_L \tilde{\phi} \psi_R + f_{ab}[\psi_L^T \tau_2 C^{-1} \Delta_L \psi_L + L \to R] + h.c.$$

- Usual Type I + Type II scenario as in MLRSM

$$M_\nu = f v_L - \frac{h_\ell f^{-1} h_\ell}{v_R} \kappa'^2.$$

- PQ charges of ψ_ℓ makes sure m_D for neutrinos is proportional to κ'
- h_ℓ is real diagonal unlike in MLRSM
- Mixings arise at tree level from Majorana mass matrix $f v_R$
- v_R > 50 TeV

Lepton mass fit

Parameters	Mixing
$h_\ell = \{m_e, m_\mu, m_\tau\}/\kappa.$ $\quad v_L = 1.8223\ eV,\ v_R = 50\ TeV$ $\quad \kappa/\kappa' = 41.1 \quad \kappa = 174.5\ GeV$	$\sin\delta_{CP} = -0.304$
$\frac{f}{10^{-2}} = \begin{pmatrix} 0.12193 & 0.91636 + 0.00765i & 3.97418 + 0.28339i \\ 0.91636 + 0.00765i & 6.57246 & -97.03846 + 1.65908i \\ 3.97418 + 0.28339i & -97.03846 + 1.65908i & 3.62771 \end{pmatrix}$	$\sin^2\theta_{13} = 0.0215$ $\sin^2\theta_{12} = 0.322$ $\sin^2\theta_{23} = 0.4275$

Masses
$m_1 = 0.00732\ eV$
$m_2 = 0.01135\ eV$
$m_3 = 0.05105\ eV$
$\Delta m^2_{21} = 7.52 \times 10^{-5}\ eV^2$
$\Delta m^2_{31} = 2.55 \times 10^{-3}\ eV^2$
$\sum m_\nu = 0.06972\ eV$
$\langle m_{\beta\beta}\rangle = 0.75 \times 10^{-3} eV$

FCNC

- As in MLRSM, ϕ_2 mediates FCNC, $m_{\phi_2} > 10TeV$
- Additional FCNC from quark couplings to $\omega_{1,2}$ studied in Babu et al [arXiv:1311.4101 [hep-ph]] which puts bounds on couplings g that are satisfied for $M_\omega \sim 10TeV$.
- Leptonic flavor changing processes are also consistent with Δ masses near $v_R = 50$ TeV

FCNC bounds on colored scalars

E. C. F. S. Fortes, K. S. Babu and R. N. Mohapatra, arXiv:1311.4101 [hep-ph]; K. S. Babu, P. S. Bhupal Dev, E. C. F. S. Fortes and R. N. Mohapatra, Phys. Rev. D **87**, no. 11, 115019 (2013).

Comments and conclusion

- Leptonic PQ charges prevent proton decay
- lightest N $\sim$ 0.1 TeV with the largest mixing $V_{eNe} \sim 10^{-6}$
- Quasi-degenerate right handed neutrinos could lead to leptogenesis
- Best-fit $\sum m_\nu = 0.07$eV can be tested in LSST and EUCLID mission
- In conclusion, we provide a combination of left-right and Peccei-Quinn symmetry to explain the flavor alignment of quarks

THANK YOU