

# Flavored axions and the flavor problem

Eduardo Rojas Peña

In Collaboration with: R. Martinez, Y. Giraldo, J.C. Salazar.

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# Outline

- CP problem
- Five texture-zero mass matrices
- Particle content
- Minimal Higgs content
- Effective Lagrangian
- Low Energy constraints
- Conclusions

# The CP problem

- In the limit  $m_f \rightarrow 0$  the QCD lagrangian has the symmetry  $U(N)_V \times U(N)_A$  where the up and down masses satisfy  $m_u, m_d \ll \Lambda_{\text{QCD}}$ , one expect that the strong interactions to be approximately  $U(2)_V \times U(2)_A$  invariant
- Experimentally  $U(2)_V = SU(2)_V \times U(1)_V \equiv \text{Isospin} \times \text{Baryon \#}$  however, quark condensates break  $U(1)_A$  down spontaneously

# The CP problem

- however, quark condensates break down  $U(1)_A$  spontaneously, one expects now 4 Nambu-Goldstone bosons  $(\pi, \eta)$ . Although pions are light, there is no clue of another light state in the hadronic spectrum
- Weinberg dubbed this the  $U(1)_A$  problem, suggesting that, somehow, there was no  $U(1)_A$  symmetry in QCD.

# The strong CP problem

- 't Hooft realized that the current associated with the  $U(1)_A$  symmetry is anomalous

$$\partial_\mu J_5^\mu = \frac{g^2 N}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} :$$

where  $N$  is the number of massless quarks. From this it is possible to add to the lagrangian the term:

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

# Strong CP problem

- This term produces an electric dipole moment for the neutron of order:

with  $d_n \approx e m_q / M_n^2 \theta \approx 10^{-16} \theta \text{ ecm}$

$$d_n < 2.9 \times 10^{-26} \text{ ecm}$$

which requires  $\theta < 10^{-9} - 10^{-10}$  |

why  $\theta$  is so small ?, this is the Strong CP problem.

# A solution

- Peccei and Quinn proposed a solution suggesting that the SM has an additional U(1) chiral symmetry which drives  $\theta_{\text{total}} \rightarrow 0$

# The five-texture mass matrices

- Our aim is to propose a PQ symmetry that generates this texture for the quark masses.

$$M^U = \begin{pmatrix} 0 & 0 & C_u \\ 0 & A_u & B_u \\ C_u^* & B_u^* & D_u \end{pmatrix},$$

$$M^D = \begin{pmatrix} 0 & C_d & 0 \\ C_d^* & 0 & B_d \\ 0 & B_d^* & A_d \end{pmatrix}.$$



# Minimal Higgs content

- From the Lagrangian

$$\mathcal{L} \supset - \left( \bar{q}_{Li} y_{ij}^{D\alpha} \Phi^\alpha d_{Rj} + \bar{q}_{Li} y_{ij}^{U\alpha} \tilde{\Phi}^\alpha u_{Rj} + \text{h.c.} \right),$$

it is possible to obtain the mass functions

$$M^U = \begin{pmatrix} 0 & 0 & x \\ 0 & x & x \\ x & x & x \end{pmatrix} \rightarrow \begin{pmatrix} S_{11}^{U\alpha} \neq 0 & S_{12}^{U\alpha} \neq 0 & S_{13}^{U\alpha} = 0 \\ S_{21}^{U\alpha} \neq 0 & S_{22}^{U\alpha} = 0 & S_{23}^{U\alpha} = 0 \\ S_{31}^{U\alpha} = 0 & S_{32}^{U\alpha} = 0 & S_{33}^{U\alpha} = 0 \end{pmatrix},$$
$$M^D = \begin{pmatrix} 0 & x & 0 \\ x & 0 & x \\ 0 & x & x \end{pmatrix} \rightarrow \begin{pmatrix} S_{11}^{D\alpha} \neq 0 & S_{12}^{D\alpha} = 0 & S_{13}^{D\alpha} \neq 0 \\ S_{21}^{D\alpha} = 0 & S_{22}^{D\alpha} \neq 0 & S_{23}^{D\alpha} = 0 \\ S_{31}^{D\alpha} \neq 0 & S_{32}^{D\alpha} = 0 & S_{33}^{D\alpha} = 0 \end{pmatrix},$$

where  $S_{ij}^{U\alpha} = (-x_{q_i} + x_{u_j} - x_{\phi_\alpha})$  and  $S_{ij}^{D\alpha} = (-x_{q_i} + x_{d_j} + x_{\phi_\alpha})$ .

# Minimal Higgs content

- To reproduce these mass functions at least 4 higgs doublets are needed.

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$Q_{PQ}$	$U(1)_{PQ}$
$\phi_1$	0	1	2	1/2	$s_1$	$x_{\phi_1}$
$\phi_2$	0	1	2	1/2	$s_2$	$x_{\phi_2}$
$\phi_3$	0	1	2	1/2	$-s_1 + 2s_2$	$x_{\phi_3}$
$\phi_4$	0	1	2	1/2	$-3s_1 + 4s_2$	$x_{\phi_4}$
$S$	0	1	1	0	$x_S \neq 0$	$x_S$
$Q_L$	1/2	3	0	0	$x_{Q_L} - x_{Q_R} \neq 0$	$x_{Q_L}$
$Q_R$	1/2	3	0	0		$x_{Q_R}$

TABLE III: Beyond standard model scalar and fermion fields and their respective PQ charges. The parameters  $s_1, s_2$  and  $\alpha$  are reals, with  $s_1 \neq s_2$ , where:  $s_1 = \frac{N}{9} \hat{s}_1$  and  $s_2 = \frac{N}{9} (\epsilon + \hat{s}_1)$ .

# Model particle content

- The PQ charges of quarks to reproduce the mass textures are

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$Q_{PQ}(i=1)$	$Q_{PQ}(i=2)$	$Q_{PQ}(i=3)$	$U(1)_{PQ}$
$q_{Li}$	1/2	3	2	1/6	$-2s_1 + 2s_2 + \alpha$	$-s_1 + s_2 + \alpha$	$\alpha$	$x_{q_i}$
$u_{Ri}$	1/2	3	1	2/3	$s_1 + \alpha$	$s_2 + \alpha$	$-s_1 + 2s_2 + \alpha$	$x_{u_i}$
$d_{Ri}$	1/2	3	1	-1/3	$2s_1 - 3s_2 + \alpha$	$s_1 - 2s_2 + \alpha$	$-s_2 + \alpha$	$x_{d_i}$

TABLE II: The columns 6-8 are the PQ  $Q_{PQ}$  charges for the SM quarks in each family. The subindex  $i = 1, 2, 3$  stands for the family number in the interaction basis. The parameters  $s_1, s_2$  and  $\alpha$  are reals, with  $s_1 \neq s_2$ , where:  $s_1 = \frac{N}{9}\hat{s}_1$  and  $s_2 = \frac{N}{9}(\epsilon + \hat{s}_1)$ .

- by choosing the VEVs in a convenient way it is possible to reproduce the quark masses and the CKM mixing matrix.

- $Y_{ij}^{(U,D)a}$  are of the order 1

- (except for  $Y_{23}^{U3}, Y_{23}^{D3}, Y_{13}^{U1}$ )

$$\hat{v}_1 = 1.71 \text{ GeV}, \quad \hat{v}_2 = 2.91 \text{ GeV}, \quad \hat{v}_3 = 174.085 \text{ GeV}, \quad \hat{v}_4 = 13.3 \text{ MeV}.$$

# Effective Lagrangian

- $$\mathcal{L} = (D_\mu \Phi^\alpha)^\dagger D^\mu \Phi^\alpha + \sum_\psi i \bar{\psi} \gamma^\mu D_\mu \psi + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

$$- \left( \bar{q}_{Li} y_{ij}^{D\alpha} \Phi^\alpha d_{Rj} + \bar{q}_{Li} y_{ij}^{U\alpha} \tilde{\Phi}^\alpha u_{Rj} + \bar{\ell}_{Li} y_{ij}^{E\alpha} \Phi^\alpha e_{Rj} + \bar{\ell}_{Li} y_{ij}^{N\alpha} \tilde{\Phi}^\alpha \nu_{Rj} + \text{h.c.} \right)$$

$$+ c_a \Phi^\alpha O_{a\Phi^\alpha} + c_1 \frac{\alpha_1}{8\pi} O_B + c_2 \frac{\alpha_2}{8\pi} O_W + c_3 \frac{\alpha_3}{8\pi} O_G,$$

where

- $$O_{a\Phi} = i \frac{\partial^\mu a}{\Lambda} \left( (D_\mu \Phi^\alpha)^\dagger \Phi^\alpha - \Phi^{\alpha\dagger} (D_\mu \Phi^\alpha) \right), \quad O_B = -\frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu},$$

$$O_W = -\frac{a}{\Lambda} W_{\mu\nu}^a \tilde{W}^{a\mu\nu}, \quad O_G = -\frac{a}{\Lambda} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}.$$

# Effective Lagrangian

- It is possible to obtain the dimension five effective lagrangians by means of the non-linear transformation

$$\Phi^\alpha \longrightarrow e^{i\frac{x\Phi^\alpha}{\Lambda}a} \Phi^\alpha,$$

$$\psi_L \longrightarrow e^{i\frac{x\psi_L}{\Lambda}a} \psi_L,$$

$$\psi_R \longrightarrow e^{i\frac{x\psi_R}{\Lambda}a} \psi_R,$$

# Down quark Vector and axial couplings

- $$\Delta\mathcal{L}_{KD} + \Delta\mathcal{L}_{YD} \equiv -\partial_\mu a \bar{d}_i \gamma^\mu \left( g_{ad_i d_j}^V + \gamma^5 g_{ad_i d_j}^A \right) d_j.$$

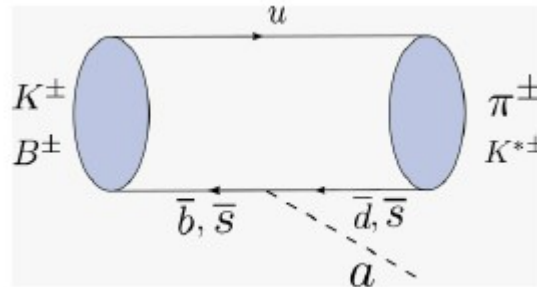
$$g_{ad_i d_j}^{V,A} = \frac{1}{2f_a c_3^{\text{eff}}} \left( 2\Delta_{V,A}^{Dij} + \frac{\hat{v}\Delta_\Phi^{\gamma 1} Y_{V,A}^{D\gamma ij}}{(m_i^D \mp m_j^D)} \right), \quad (35)$$

where  $\Delta_{V,A}^{Dij} = \Delta_{RR}^{Dij}(d) \pm \Delta_{LL}^{Dij}(q)$  with  $\Delta_{LL}^{Fij}(q) = \left( U_L^D x_q U_L^{D\dagger} \right)^{ij}$  and  $\Delta_{RR}^{Fij}(d) = \left( U_R^D x_d U_R^{D\dagger} \right)^{ij}$ . The parameters associated with the FCNC due to the differences between the Higgs charges are:  $\Delta_\Phi^{\gamma\beta} = (R x_\Phi R^T)^{\gamma\beta}$ ,  $\hat{v} = v/\sqrt{2}$  and  $Y_{V,A}^{D\gamma ij} = \left( Y_{ij}^{D\gamma} \mp Y_{ij}^{D\gamma\dagger} \right)$ . The term with  $\gamma = 1$  does not contribute to the FCNC since  $Y^{D1} = \frac{2}{v} m^D$  is a diagonal

# Constraints from Semileptonic decays

$$\Gamma(K^+ \rightarrow \pi^+ a) = \frac{m_K^3}{16\pi} \left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \lambda_{K\pi a}^{1/2} f_0^2(m_a^2) |g_{ads}^V|^2.$$

$$\Gamma(B \rightarrow K^* a) = \frac{m_B^3}{16\pi} \lambda_{BK^* a}^{3/2} A_0^2(m_a^2) |g_{asb}^A|^2.$$





# Constraints from semileptonic decays

Collaboration	upper bound
E949+E787 [48, 49]	$\mathcal{B}(K^+ \rightarrow \pi^+ a) < 0.73 \times 10^{-10}$
CLEO [50]	$\mathcal{B}(B^\pm \rightarrow \pi^\pm a) < 4.9 \times 10^{-5}$
CLEO [50]	$\mathcal{B}(B^\pm \rightarrow K^\pm a) < 4.9 \times 10^{-5}$
BELLE [51]	$\mathcal{B}(B^\pm \rightarrow \rho^\pm a) < 21.3 \times 10^{-5}$
BELLE [51]	$\mathcal{B}(B^\pm \rightarrow K^{*\pm} a) < 4.0 \times 10^{-5}$

(36)

TABLE IV: These inequalities come from the window for new physics in the branching ratio uncertainty of the meson decay in a pair  $\bar{\nu}\nu$ .

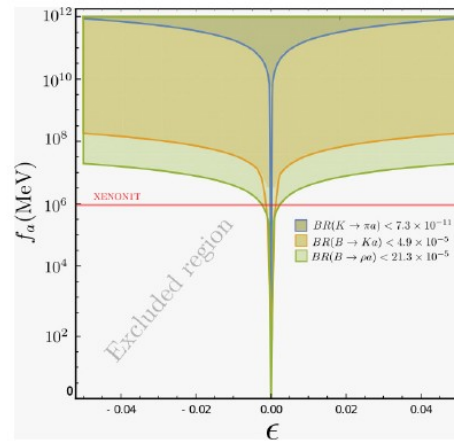


FIG. 2: Allowed regions by semileptonic meson decays.

# Conclusions

- In this work we have proposed a PQ symmetry that gives rise to Hermitian mass matrices with five texture-zeros. This texture can adjust in a non-trivial way the six masses of the quarks and the three CKM mixing angles and the CP violating phase.
- we showed that this texture requires at least four Higgs doublets to be generated from a PQ symmetry. We proposed a general parameterization for the PQ charges which is consistent with the texture.

# Conclusions

- We calculated the FCNC coming from the effective Lagrangian of interaction between the Yukawa term and the axion. This calculation poses some technical problems due to the multi-Higgs sector. To solve this, we proposed a generalized Georgi rotation for an arbitrary number of Higgs doublets.
- As a bonus, we showed that our model can adjust the axion mass required to explain the anomaly recently reported by XENON1T~\cite{Aprile:2020tmw}.