Flavored Axions and the flavor problem

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The five texture-zero mass matrices:

$$M^U = \begin{pmatrix} 0 & 0 & |C_u|e^{i\phi_{C_u}} \\ 0 & A_u & |B_u|e^{i\phi_{B_u}} \\ |C_u|e^{-i\phi_{C_u}} & |B_u|e^{-i\phi_{B_u}} & D_u \end{pmatrix},$$

$$M^D = \begin{pmatrix} 0 & |C_d| & 0 \\ |C_d| & 0 & |B_d| \\ 0 & |B_d| & A_d \end{pmatrix}, \quad (1)$$

$$M^N = \begin{pmatrix} 0 & |C_\nu|e^{ic_\nu} & 0 \\ |C_\nu|e^{-ic_\nu} & E_\nu & |B_\nu|e^{ib_\nu} \\ 0 & |B_\nu|e^{-ib_\nu} & A_\nu \end{pmatrix}$$

$$M^E = \begin{pmatrix} 0 & |C_\ell| & 0 \\ |C_\ell| & 0 & |B_\ell| \\ 0 & |B_\ell| & A_\ell \end{pmatrix}, \quad (2)$$

We have shown that the analyzed texture (1) needs at least four Higgs doublets, to reproduce the five-texture zeros with the PQ symmetry.

The same Higgs doublets reproduce satisfactorily (2) .

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PQ symmetry and the minimal particle content

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

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$	Q_{PQ}
Φ_1	0	1	2	1/2	x_{ϕ_1}	$s_1 \in$ reals
Φ_2	0	1	2	1/2	x_{ϕ_2}	$s_2 \in$ reals
Φ_3	0	1	2	1/2	x_{ϕ_3}	$-s_1+2s_2$
Φ_4	0	1	2	1/2	x_{ϕ_4}	$-3s_1+4s_2$
S_1	0	1	1	0	x_{s_1}	$x_{s_1}=s_1-s_2\neq 0$
S_2	0	1	1	0	x_{s_2}	$x_{s_2}=x_{Q_R}-x_{Q_L}\neq 0$
Q_L	1/2	3	0	0	x_{Q_L}	$x_{Q_L}\in$ reals
Q_R	1/2	3	0	0	x_{Q_R}	$x_{Q_R}\in$ reals

$$Q_{PQ}(s_1,N,\alpha)(\psi)=\frac{N}{9}\left(\hat{s}_1 Q_{PQ}^{s_1}(\psi)+(\epsilon+\hat{s}_1)Q_{PQ}^{s_2}(\psi)\right)+\alpha Q_{PQ}^{V_q}(\psi)+\alpha' Q_{PQ}^{V_l}(\psi),$$

with $\epsilon=(1-A_Q/N)$ and $A_Q=x_{Q_L}-x_{Q_R}$

$\epsilon\neq 0.$

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Naturalness of Yukawa couplings

$$M^D = \begin{pmatrix} 0 & |y_{12}^{D4}|\hat{v}_4 & 0 \\ |y_{12}^{D4}|\hat{v}_4 & 0 & |y_{23}^{D3}|\hat{v}_3 \\ 0 & |y_{23}^{D3}|\hat{v}_3 & y_{33}^{D2}\hat{v}_2 \end{pmatrix} \qquad M^U = \begin{pmatrix} 0 & 0 & y_{13}^{U1}\hat{v}_1 \\ 0 & y_{22}^{U1}\hat{v}_1 & y_{23}^{U2}\hat{v}_2 \\ y_{13}^{U1^*}\hat{v}_1 & y_{23}^{U2^*}\hat{v}_2 & y_{33}^{U3}\hat{v}_3 \end{pmatrix}$$

$$\hat{v}_i = v_i/\sqrt{2}$$

By setting various Yukawa couplings close to 1 in the quarks sector (except y_{23}^{U2}, y_{23}^{D3} and y_{13}^{U1}) we obtain:

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

$$(v_1^2 + v_2^2 + v_3^2 + v_4^2) = (246.24\,\mathrm{GeV})^2$$

Mass spectrum for the scalar sector:

The mass spectrum of the scalar fields is above the TeVs scale, except the SM Higgs which was set to 125 GeV. The pseudoscalar sector (CP odd fields) have two zero mass eigenstates, the axion field and the Goldstone boson which is absorbed by the longitudinal component of the MZ boson. A similar result is achieved in the charged sector where it is possible to identify the two Goldstone bosons needed to give mass to the SM $W^{\pm}$ fields.

$$f_a = \frac{v_S}{2N}$$

$$v_S \approx 10^6 \mathrm{GeV}.$$

$$\begin{aligned}
\text{CP even} &= \{1.73 \times 10^6, 1. \times 10^6, 6.54 \times 10^3, 1.97 \times 10^3, \\
&\qquad 1.09 \times 10^3, 125\}, \\
\text{CP odd} &= \{6.54 \times 10^3, 1.97 \times 10^3, 1.09 \times 10^3, 0, 0, m_{\zeta_{S_2}}\}, \\
\text{Charged fields} &= \{6.54 \times 10^3, 1.97 \times 10^3, 1.11 \times 10^3, 0\}.
\end{aligned}$$

The most general Lagrangian for the interaction of four Higgs doublets Φ_α with the quarks of the SM is given by

$$\mathcal{L} = -\bar{q}_L^{\prime i} \Phi_\alpha y_{ij}^{D\alpha} d_R^{\prime j} - \bar{q}_L^{\prime i} \tilde{\Phi}_\alpha y_{ij}^{U\alpha} u_R^{\prime j} + \text{h.c},$$

where a sum is assumed on repeated indices. Here i, j run over $1, 2, 3$ and α over $1, 2, 3, 4$. The Higgs boson doublet fields are parameterized as follows:

$$\Phi_\alpha = \begin{pmatrix} \phi_\alpha^+ \\ \frac{v_\alpha + h_\alpha + i\eta_\alpha}{\sqrt{2}} \end{pmatrix}, \qquad \tilde{\Phi}_\alpha = i\sigma_2 \Phi_\alpha^*.$$

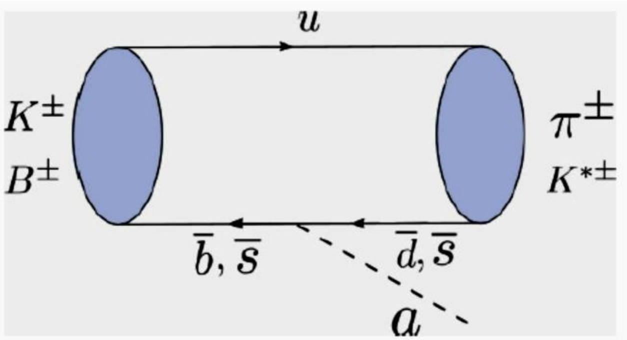
Georgi Rotation:

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \end{pmatrix} = R_1(\beta_1) R_2(\beta_2) R_3(\beta_3) \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \Phi_4 \end{pmatrix} =: H_\beta \equiv R_{\beta\alpha} \Phi_\alpha,$$

$$\langle H_1^0 \rangle = \sqrt{v_1^2 + v_2^2 + v_3^2 + v_4^2} \equiv v,$$

$$\langle H_2^0 \rangle = 0, \qquad \langle H_3^0 \rangle = 0, \qquad \langle H_4^0 \rangle = 0.$$

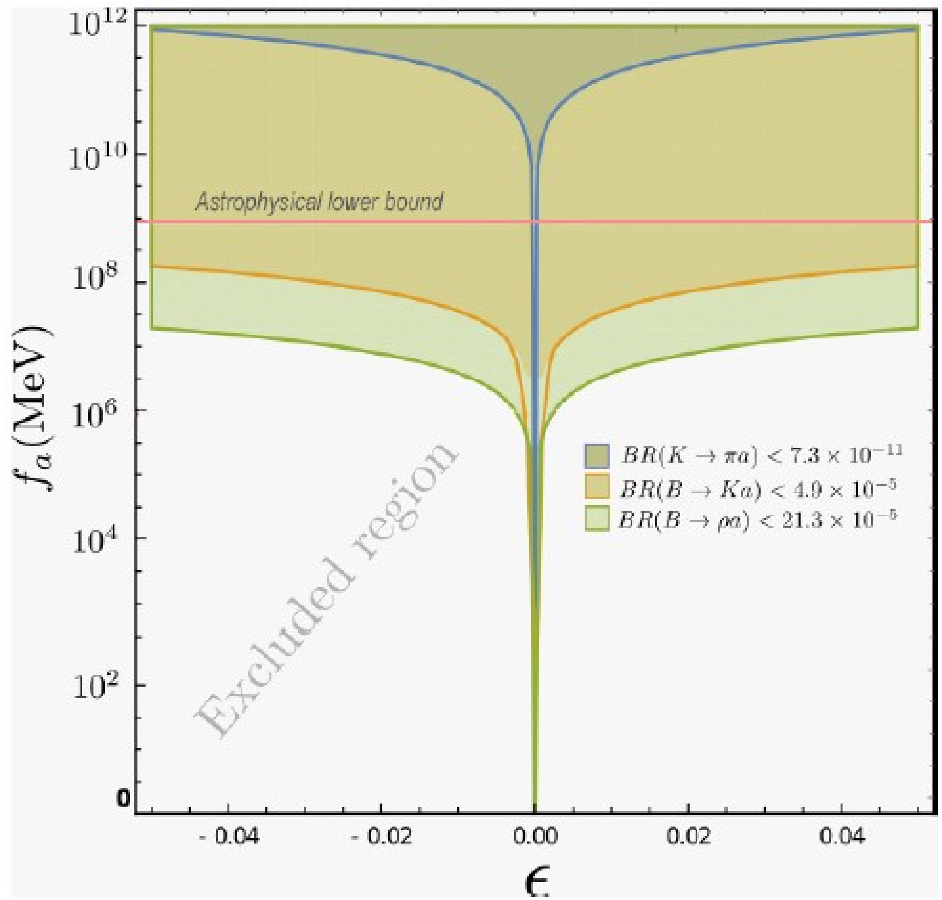
LOW ENERGY CONSTRAINTS



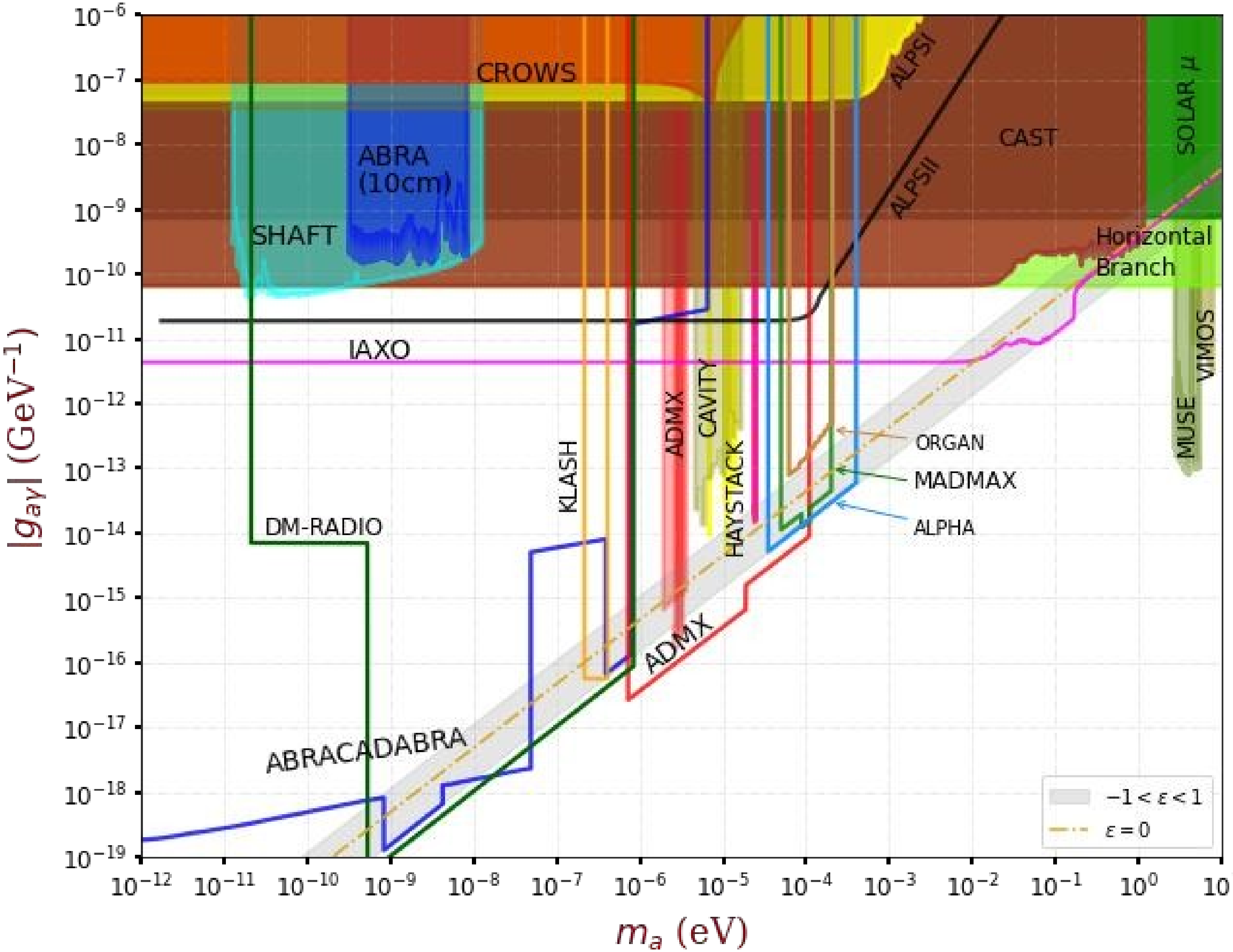
$$\Gamma(K^\pm \to \pi^\pm a) = \frac{m_K^3}{16\pi}\left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \lambda_{K\pi a}^{1/2} f_0^2(m_a^2)|g_{ads}^V|^2$$

$$g_{ad_id_j}^{V,A} = \frac{1}{2f_a c_3^{\text{eff}}}\Delta_{V,A}^{Dij},$$

Collaboration	Upper bound
E949+E787 [148, 149]	$\mathcal{B}\left(K^+ \to \pi^+ a\right) < 0.73 \times 10^{-10}$
CLEO [150]	$\mathcal{B}\left(B^\pm \to \pi^\pm a\right) < 4.9 \times 10^{-5}$
CLEO [150]	$\mathcal{B}\left(B^\pm \to K^\pm a\right) < 4.9 \times 10^{-5}$
BELLE [151]	$\mathcal{B}\left(B^\pm \to \rho^\pm a\right) < 21.3 \times 10^{-5}$
BELLE [151]	$\mathcal{B}\left(B^\pm \to K^{*\pm} a\right) < 4.0 \times 10^{-5}$



CONSTRAINTS ON THE AXION-PHOTON COUPLING



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