A flavoured invisible axion

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Introduction: the Strong CP phase

$\mathcal{L}_{\text{QCD}}$ has an approximate global chiral symmetry
$\mathrm{SU}(3)_V \otimes \mathrm{SU}(3)_A \otimes \mathrm{U}(1)_B \otimes \mathrm{U}(1)_A \rightarrow \mathrm{SU}(3)_V \otimes \mathrm{U}(1)_B$

9 pseudo-Goldstone bosons expected, however the η' is "heavy"

non-perturbative QCD effects explicitly break the $\mathrm{U}(1)_A$ symmetry

[G. 't Hooft, 1976]

$$\mathcal{L}_\theta = \bar{\theta} \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}$$

$$\bar{\theta} = \underline{\theta} + \underline{\arg\left[\det\left(M_{\text{quark}}\right)\right]}$$

From QCD   From the Yukawa sector

- ✓ The $\mathrm{U}(1)_A$ problem is solved. Source for the η' mass
- ✗ For $\bar{\theta} \neq 0$, $\mathcal{L}_\theta$ violates T and P, and therefore also CP.
  From neutron EDM $|\bar{\theta}| \lesssim 10^{-11}$ [Baker et al., 2006] **Why??**

Interesting proposal: Promote $\bar{\theta}$ to a dynamical field

[Peccei, Quinn (1977)]

$\Rightarrow$ new light particle in the spectrum, the **axion**

[Weinberg & Wilczek (1978)]

"I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving axial currents" F. Wilczek (The Birth of Axions, 1991)

Introduction: Axion models

General features

- PQ symmetry: global QCD anomalous and chiral $U(1)_{\text{PQ}}$
- New particle: the axion

Original Peccei-Quinn implementation [Peccei, Quinn (1977)]

- Two Higgs doublets with the PQ symmetry enforcing NFC
- The PQ and the electroweak scales are the same

✗ Ruled out by experiment

Invisible axion models (extra scalar singlet $\sqrt{2}\langle S\rangle = v_{\text{PQ}} \gg v$)

✓ Interesting features: Dark matter, neutrino masses...

- KSVZ: SM (PQ blind) + $Q_{L,R}$ + S [Kim (1979); Shifman, Vainshtein, Zakharov (1980)]
- DFSZ: 2HDM + S [Zhitnitskii (1980); Dine, Fischler, Srednicki (1981)]

I will work on DFSZ-like extensions, i.e **MHDM + S**

Introduction: Natural Flavor Conservation (NFC)

Extend the scalar sector by adding extra doublets

✗ Uncontrolled FCNCs

$$-\mathcal{L}_{\mathsf{Y}} = \overline{Q_L^0}\ [\Gamma_1\,\Phi_1 + \Gamma_2\,\Phi_2]\, d_R^0 + \overline{Q_L^0}\ [\Delta_1\,\widetilde{\Phi}_1 + \Delta_2\,\widetilde{\Phi}_2] u_R^0 + \text{h.c.}$$

Warning! FCNCs!

Protection by symmetry [Weinberg, Glashow (1977); Pachos (1997)]

Introduce a $\mathcal{Z}_2$ symmetry that only allows one Yukawa in each sector

Model	up	down	lepton
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

✓ Free of FCNCs

✓ PQ symmetry: DFSZ invisible axion model

(only for type II and flipped)

Motivation: Branco–Grimus–Lavoura model (BGL)

Controlled FCNCs [Branco, Grimus, Lavoura (1996)]

Allow FCNCs in one sector controlled by the CKM matrix

- ✓ Strong suppression of FCNCs due to the off-diagonal CKM matrix elements
  [Botella, Branco, Carmona, Nebot, Pedro, Rebelo (2014); Bhattacharyya, Das, Kundu (2014)]
- ✓ Imposed by a symmetry (discrete or continuous)
  $\Rightarrow$ Stable under RGE [Botella, Branco, Nebot, Rebelo (2011)]
- ✗ Accidental symmetry in the Higgs potential
  $\Rightarrow$ Undesired pseudo-Goldstone boson

Solutions:

- Add additional soft breaking terms to the scalar potential
- Add extra singlets to the scalar sector

Opportunity: The PQ symmetry is responsible for the BGL Yukawa structure and the pseudo-Goldstone boson is the axion

[AC, Fuentes, Serodio (2014)]


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y Extractos de naranja
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EL VERDADERO ARRANCAGRASA
Limòn
CONT. NETO. 800 cm3
NUEVO MAXIMO PODER
AXION
EL VERDADERO ARRANCAGRASA
BICARBONATO
y Extractos de toronja
CONT. NETO. 800 cm3
NUEVO MAXIMO PODER
AXION
EL VERDADERO ARRANCAGRASA
OXY
Plus
BICARBONATO
CONT. NETO. 800 cm3
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AXION
EL VERDADERO ARRANCAGRASA
Lima
CONT. NETO. 800 cm3

Why is BGL safe from large FCNCs?

$$\text{Up Yukawas:}\quad \Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\text{Down Yukawas:}\quad \Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

In the mass basis

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_1}{v_2} + \frac{v_2}{v_1} \right) U_{dL}^\dagger \Gamma_2 U_{dR}$$

$$[N_d]_{ij} = \frac{v_2}{v_1} [D_d]_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) (V_{\mathsf{CKM}})^*_{3i} (V_{\mathsf{CKM}})_{3j} [D_d]_{jj}$$

Effective suppression of scalar FCNCs effects in flavour transitions (meson mixing, . . .)

[Botella, Branco, Carmona, Nebot, Pedro, Rebelo (2014)]

[Bhattacharyya, Das, Kundu (2014)]

Can we add an axion to this setup?

Finding the anomalous implementation

- Up sector block diagonal

$$\mathcal{S}_L = \text{diag}\left(1, 1, e^{iX_{tL}\,\alpha}\right)\ , \quad \mathcal{S}_R^u = \text{diag}\left(e^{iX_{uR}\,\alpha}, e^{iX_{uR}\,\alpha}, e^{iX_{tR}\,\alpha}\right)$$

- Down sector unconstrained

$$\mathcal{S}_R^d = e^{iX_{dR}\alpha}\,\mathbb{I}$$

Yukawa phase transformation matrix

$$\Theta_u = \alpha\begin{pmatrix} X_{uR} & X_{uR} & X_{tR} \\ X_{uR} & X_{uR} & X_{tR} \\ X_{uR}-X_{tL} & X_{uR}-X_{tL} & X_{tR}-X_{tL} \end{pmatrix}$$

$$\Theta_d = \alpha\begin{pmatrix} X_{dR} & X_{dR} & X_{dR} \\ X_{dR} & X_{dR} & X_{dR} \\ X_{dR}-X_{tL} & X_{dR}-X_{tL} & X_{dR}-X_{tL} \end{pmatrix}$$

BGL 2HDM has no $\mathrm{U}(1)_{\mathsf{PQ}}[\mathrm{SU}(3)_C]^2$ anomaly (not good PQ symmetry)

We need at least 3 Higgs doublets

3HFPQ model

Lagrangian

$$-\mathcal{L}_{\mathsf{Y}} = \overline{Q_L^0}\,[\Gamma_1\,\Phi_1 + \Gamma_3\,\Phi_3]\,d_R^0 + \overline{Q_L^0}\,[\Delta_1\,\widetilde{\Phi}_1 + \Delta_2\,\widetilde{\Phi}_2]u_R^0$$
$$+\,\overline{L_L^0}\,[\Pi_2\,\Phi_2 + \Pi_3\,\Phi_3]\,l_R^0 + \overline{L_L^0}\,\Sigma_3\,\widetilde{\Phi}_3 N_R^0 + \overline{(\mathbf{N_R^0})^c}\mathbf{A}\mathbf{N_R^0}\mathbf{S}^* + \text{h.c.}$$

Field transformations

$$X_L^Q = (0,0,-2)\,,\quad X_R^u = (5/2, 5/2, -1/2)\,,\quad X_R^d = -5/2$$
$$X_L^\ell = (0,0,1)\,,\quad X_R^\ell = -1/2\,,\quad X_R^N = 1/2\,,\quad X_S = 1$$

Textures

$$\Gamma_1 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}\,,\qquad \Gamma_2 = 0\,,\qquad \Gamma_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}\,,$$

$$\Delta_1 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}\,,\qquad \Delta_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}\,,\qquad \Delta_3 = 0\,,$$

The leptonic sector

$$\Pi_1 = 0\,, \quad \Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}\,, \quad \Pi_3 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}\,,$$

Two right-handed neutrinos

$$\Sigma_3 = \begin{pmatrix} \times & \times \\ \times & \times \\ 0 & 0 \end{pmatrix}$$

$$m_\nu \simeq -\frac{v_3^2}{2\sqrt{2}v_{\mathsf{PQ}}}\Sigma_3 A^{-1} {\Sigma_3}^T = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Neutrino masses via type I see-saw mechanism. One massless light neutrino.

3HFPQ. Model properties

- No FCNCs in the up-quark sector
- FCNCs in the down-quark sector under control

$$\left(N_d'\right)_{ij} = (D_d)_{ij} - \frac{v^2}{v_3^2}(V_{\text{CKM}}^\dagger)_{i3}(V_{\text{CKM}})_{3j}(D_d)_{jj}$$

$$(N_d)_{ij} = \frac{v_2}{v_1}(D_d)_{ij} - \frac{v_2}{v_1}(V_{\text{CKM}}^\dagger)_{i3}(V_{\text{CKM}})_{3j}(D_d)_{jj}$$

- FCNCs in the charged lepton sector under control

$$\left(N_e'\right)_{ij} = -\frac{(v_1^2+v_2^2)}{v_3^2}(D_e)_{ij} + \frac{v^2}{v_3^2}(U_{\text{PMNS}}^\dagger)_{i3}(U_{\text{PMNS}})_{3j}(D_e)_{jj}$$

$$(N_e)_{ij} = -\frac{v_1}{v_2}(U_{\text{PMNS}}^\dagger)_{i3}(U_{\text{PMNS}})_{3j}(D_e)_{jj}$$

Axion properties

The axion mass is suppressed by the PQ symmetry breaking scale

[Weinberg (1978)]

$$m_a \simeq 6 \text{ meV} \times \left(\frac{10^9 \text{ GeV}}{v_{\text{PQ}}} \right)$$

The axion coupling to photons is described by the Lagrangian

$$\frac{\alpha}{8\pi v_{\text{PQ}}} C_{a\gamma}^{\text{eff}} \, a \, F_{\mu\nu} \widetilde{F}^{\mu\nu} \equiv \frac{1}{4} g_{a\gamma} \, a \, F_{\mu\nu} \widetilde{F}^{\mu\nu} \, .$$

$$C_{a\gamma}^{\text{eff}} \simeq \underline{26/3} \qquad - \qquad 2$$

model depedent — mixing with π^0

Inherent correlation between the axion-photon coupling and its mass

$$(m_a/1 \, \text{eV}) \simeq 0.5 \, \xi \, g_{10} \, ,$$

where $g_{10} = |g_{a\gamma}|/(10^{-10} \, \text{GeV}^{-1})$ and $\xi = 1/|C_{a\gamma}^{\text{eff}}|$.
In the DFSZ (type II and flipped) and KSVZ models $\xi \sim 1.4 \, (0.8)$ and 0.5

Flavour bounds

The axion mediates flavour changing transitions

$$\mathcal{L}_{\text{FCNC}} = \frac{\partial_\mu a}{2 v_{\text{PQ}}} \left[\bar{\mu} \gamma^\mu \left(g^V_{\mu e} + \gamma_5 \, g^A_{\mu e} \right) e + \bar{s} \gamma^\mu \left(g^V_{sd} + \gamma_5 \, g^A_{sd} \right) d \right] + h.c.$$

Flavour changing axion couplings controlled by elements of the fermion mixing matrices

$$g^{V,A}_{\mu e} = U^*_{\tau 2} U_{\tau 1} \sim 2.4 \times 10^{-1} \qquad g^{V,A}_{sd} = -2 V^*_{ts} V_{td} \sim 6.9 \times 10^{-4}$$

$$\mu^+ \to e^+ a \gamma \longrightarrow m_a \leq 12 \text{ meV} \qquad K^+ \to \pi^+ a \longrightarrow m_a \leq 18 \text{ meV}$$

[Bolton et al. (1988)] [Adler et al. E787 Collaboration (2002)]

Robust bounds from rare muon and kaon decay searches

(only one insertion of the axion couplings $\propto 1/v_{\text{PQ}}$)

Axion astrophysical bounds

Bound from white-dwarfs (WD)

$$\mathcal{L}_{ea} = g_{ee}^{A} \frac{\partial_\mu a}{2 v_{\mathrm{PQ}}} \bar{e}\gamma^\mu \gamma_5 e \quad \Rightarrow \quad m_a \lesssim 1.5/|g_{ee}^{A}|\, \mathrm{meV}$$

[Raffelt (2008); Bertolami et al. (2014)]

$$g_{ee}^{A} = -2 + |U_{\tau 1}|^2 + \frac{v_2^2 + 2v_3^2}{v^2} \qquad |g_{ee}^{A}| \in [0, 1.8]$$

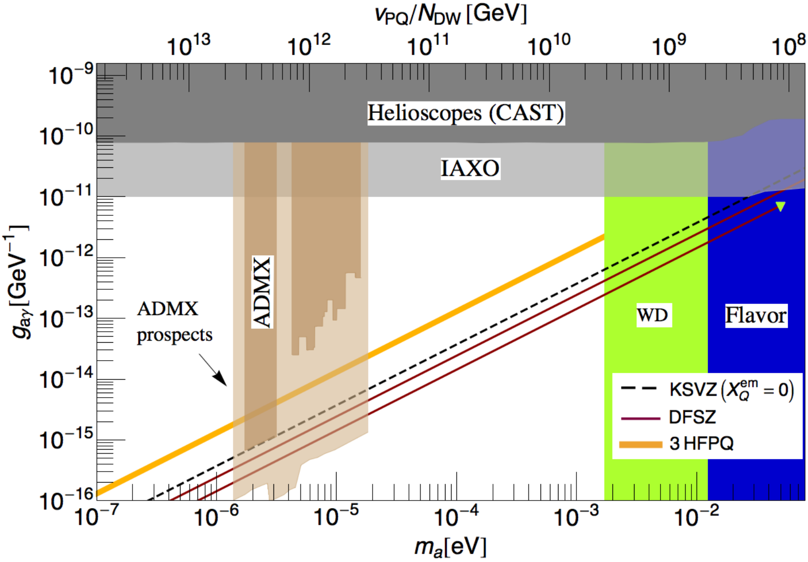
In the top-vev dominance regime, i.e $v_2 \simeq v$: $m_a \lesssim 1.7$ meV

Experimental constraints on $\mathbf{g_{a\gamma}}$:

- Helioscopes: CERN Axion Solar Telescope (CAST), International Axion Observatory (IAXO)

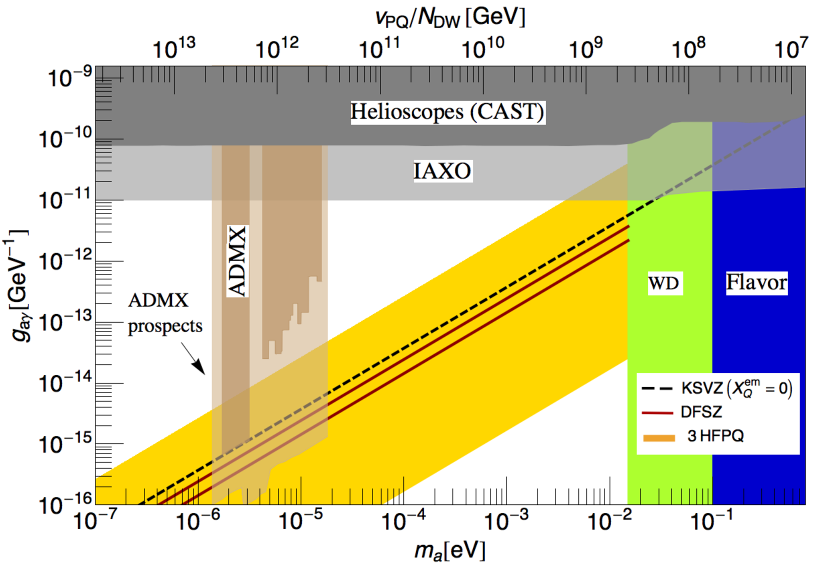
  [Andriamonje et al. (2007); Irastorza et al. (2011)]

- Axion Dark Matter experiment (ADMX) [Asztalos et al. (2010)]



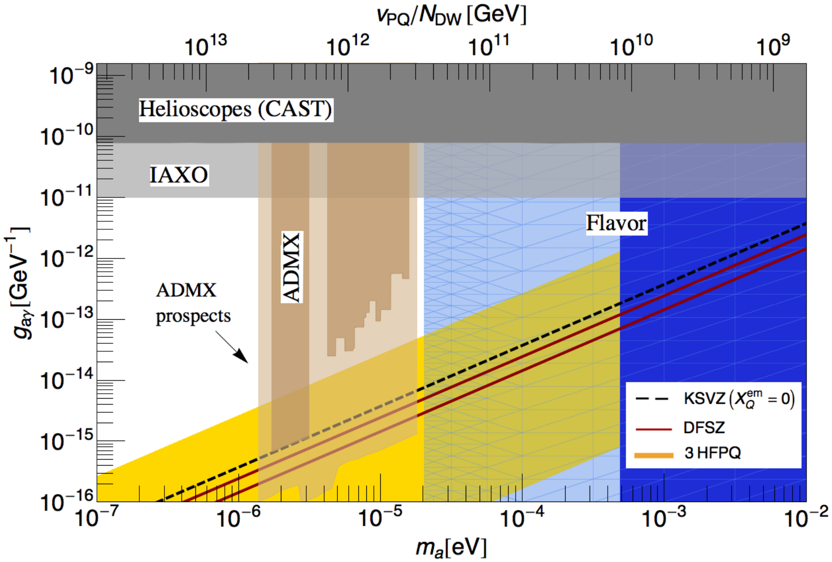
v_{PQ}/N_{DW} [GeV]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
Helioscopes (CAST)
IAXO
ADMX
ADMX prospects
WD
Flavor
KSVZ ($X_Q^{em} = 0$)
DFSZ
3 HFPQ
$g_{a\gamma}$[GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
m_a[eV]

Model variations



v_{PQ}/N_{DW} [GeV]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
Helioscopes (CAST)
IAXO
ADMX
ADMX prospects
WD
Flavor
KSVZ ($X_Q^{em} = 0$)
DFSZ
3 HFPQ
$g_{a\gamma}$[GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
m_a[eV]

Permuting flavors



models singling out the up or charm quarks

$$|V_{ud}^* V_{us}|^2 \sim |V_{cd}^* V_{cs}|^2 \gg |V_{td}^* V_{ts}|^2$$

The elephant in the room

Axion models involve physics at two disparate mass scales associated to the scalar sector $v_{\text{PQ}} \gg v$

Which symmetry could be protecting the EW scale in these models?

I consider here two possibilities:

- Poincare protection [Foot, Kobakhidze, McDonald, Volkas (2014)]
- An ultraweak sector [Allison, Hill, Ross (2014)]

Poincare protection

Consider the DFSZ invisible axion model:
$\langle\Phi_1^0\rangle = v_1/\sqrt{2}$, $\langle\Phi_2^0\rangle = v_2/\sqrt{2}$, $\langle S\rangle = v_{\mathsf{PQ}}/\sqrt{2}$

Successful EWSB requires $(v_1^2 + v_2^2)^{1/2} = v \simeq 246$ GeV and we need $v/v_{\mathsf{PQ}} \ll 1$ to make the axion invisible.

The Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}+\Phi_2} + \mathcal{L}_{\mathsf{mix}} + \mathcal{L}_S$$

$$-\mathcal{L}_{\mathsf{mix}} = \lambda_{1S}|\Phi_1|^2|S|^2 + \lambda_{2S}|\Phi_2|^2|S|^2 + \kappa\Phi_1^\dagger\Phi_2 S^2 + \mathrm{h.c.}$$

The hierarchy $v/v_{\mathsf{PQ}} \ll 1$ is radiatively stable if the mixing couplings are suppressed:

$$\lambda_{1S}, \lambda_{2S}, \kappa \lesssim \frac{(10^2\ \mathsf{GeV})^2}{M_S^2} \ll 1$$

this is technically natural because the two sectors decouple in the limit $\lambda_{1S}, \lambda_{2S}, \kappa \to 0$, giving an enhanced Poincare symmetry $\mathcal{G}_P^{SM+\Phi_2} \otimes \mathcal{G}_P^S$ in the theory. [Foot et al. (2014)]

An ultraweak sector

Lets add a real scalar gauge singlet σ to the SM and impose Classical Scale Invariance in the theory

$$V(H,\sigma) = \frac{\lambda}{2}(H^\dagger H)^2 + \frac{\zeta_1}{2}\sigma^2 H^\dagger H + \frac{\zeta_2}{4}\sigma^4$$

We assume that the coefficients ζ_i are ultraweak, $|\zeta_i| \lesssim v^2/f^2 \ll 1$

(f plays the role of v_{PQ})

σ will acquire a vev $\langle\sigma\rangle = f$ via the Coleman-Weinberg mechanism (scale invariance is broken at the quantum level)

Consistency of the CW mechanism requires $|\zeta_2| \ll |\zeta_1| \ll 1$.

Spontaneous EWSB is triggered and one obtains

$$\frac{|\zeta_1|}{2\lambda} = \frac{v^2}{f^2}\,, \qquad m_h^2 = 2\lambda v^2$$

One also gets a dilaton $m_\sigma \simeq 0.179 \times (10^{10}\ \text{GeV}/f)$ keV

An ultraweak sector

The technical naturalness of the ultra-weak sector is understood in terms of a custodial shift symmetry for the scalar gauge singlet field. [Allison, Hill, Ross (2014)]

In the limit $\zeta_i \to 0$ we have an enhanced shift symmetry of the action.

Due to the custodial shift symmetry, the ζ_i couplings, as a class, are multiplicatively renormalized

$$\beta_{\zeta_1} \propto \left(6\zeta_1\zeta_2 + 6\zeta_1\lambda + 4\zeta_1^2 - \frac{3}{2}\zeta_1(3g_2^2 + g_1^2) + 6\zeta_1 g_t^2\right)$$

$$\beta_{\zeta_2} \propto \left(18\zeta_2^2 + 2\zeta_1^2\right)$$

small ζ_i couplings remain naturally small...

Conclusions

- I have shown how the idea behind the DFSZ invisible axion model can be realized with a flavored PQ symmetry.
- The invisible axion models constructed have FCNCs at tree-level and are particularly predictive since their flavor structure is determined by the fermion mixing matrices
- Rare kaon and muon decays put strong limits on a flavored invisible axion. These are complementary to limits obtained from astrophysical considerations and axion searches relying on the axion-photon coupling
- Mechanisms to protect the EW scale in invisible axion models suggest the existence of a rich scalar sector at the weak scale (avoid decoupling) and/or additional weakly coupled light particles besides the axion (pseudo-dilaton)

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