A common source for scalars: Axiflavon-Higgs unification

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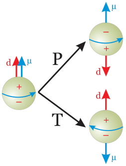
Outlook

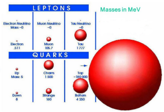
1. motivation
2. the axiflavon-Higgs
3. constraints from EWSB
4. conclusion

Motivation

many puzzles in the SM:

- strong CP problem
- Dark Matter
- flavour puzzle
- neutrino masses
- ...





$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

Seeking for a linked solution

- Peccei-Quinn as a flavor symmetry
- Froggatt-Nielsen mechanism for flavor hierarchies
- a complex scalar features the axion and the flavon [1612.08040, 1612.05492]

- including the Higgs in a unified picture [1807.10156]

Axiflavon setup

symmetries

- new global symmetry $U(1)_H$
- SM fermions are chirally charged under $U(1)_H$
- $U(1)_H$ has QCD anomaly

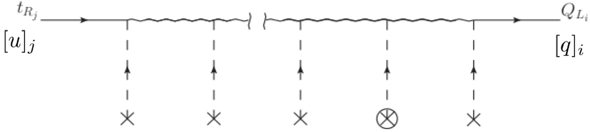
matter content

- new vector-like fermions (FN messengers)
- new complex scalar Φ, SM singlet:

$$\Phi = \frac{1}{\sqrt{2}}(f + \phi)e^{\imath a/f}$$

FN mechanism for mass generation

- FN messengers are heavy $\sim \Lambda$ and integrated out



- in the IR, effective operators look like

$$\mathcal{O} = \bar{q} \left(\frac{\Phi}{\Lambda}\right)^{[q]-[u]} \tilde{h}\, u \to m \sim v_h \left(\frac{f}{\Lambda}\right)^{[q]-[u]}$$

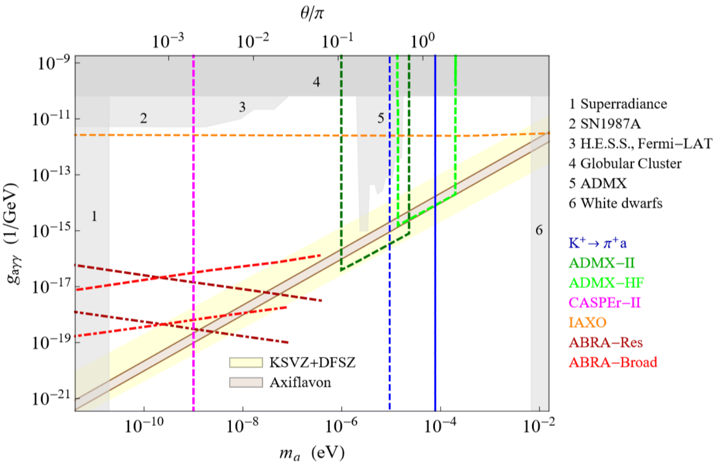
- CKM matrix

$$V_{\mathrm{CKM}\,ij} \sim \left(\frac{f}{\Lambda}\right)^{[q]_j-[q]_i}$$

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

Axion couplings

- axion couplings fixed by flavor: $g_{a\gamma\gamma} = \frac{[1.0,2.2]}{10^{16}\,\text{GeV}} \frac{m_a}{\mu\text{eV}}$



Including the Higgs

- Φ-h portal cannot be forbidden
- is it possible to increase the predictivity due to non-trivial Φ-h interplay?
- theoretically appealing to unify all the scalar degrees of freedom

- FN mechanism: $v_H \ll f \rightarrow$ suggests the Higgs as pNGB
- flavor story for elementary Goldstone-Higgs models

$SO(5)/SO(4)$ setup

symmetries

- $\mathcal{G} = SO(5) \times U(1)_H \to SO(4) = \mathcal{H}$
- $\mathcal{G}/\mathcal{H}$ decomposes as $\mathbf{1} \oplus \mathbf{4}$ under $\mathcal{H}$
- axion-Higgs unification [1208.6013]

scalars

- a single multiplet Σ transforming as $\mathbf{5}_1$ under $\mathcal{G}$,

$$\Sigma = e^{i(\sqrt{2}h_{\hat{a}}\hat{T}^{\hat{a}}+a)/f} \begin{pmatrix} H \\ (f+\phi)/\sqrt{2} \end{pmatrix}$$

- $\mathcal{G} \to \mathcal{H}$ at the scale f via a linear σ-model potential:

$$V(\Sigma, \Sigma^*) = \lambda_1 \left(\Sigma^\dagger \Sigma\right)^2 - \lambda_2 \Sigma^T \Sigma \, \Sigma^\dagger \Sigma^* - \mu^2 \Sigma^\dagger \Sigma \,.$$

$SO(5)/SO(4)$ setup

fermions

- FN messengers ξ_j as $SO(5)$ spinorial reps: $\mathbf{4}_j$ (useful for the chain)

$$-\mathcal{L} \supset \sum_j \left(\bar{\xi}_{j+1}\,\Gamma^\alpha\,\Sigma_\alpha\,\xi_j + \text{h.c.}\right) + m_j\,\bar{\xi}_j\,\xi_j$$

- SM fermions as $\mathbf{4}$ spurions Ψ^i_f:

$$-\mathcal{L} \supset \sum_{i,f} \bar{\Psi}^i_f\,\Gamma^\alpha\,\Sigma_\alpha\,\xi_j + \bar{\xi}_{j+2}\,\Gamma^\alpha\,\Sigma_\alpha\,\Psi^i_f + \bar{\Psi}^3_{q_L}\,\Gamma^\alpha\,\Sigma_\alpha\,\Psi^3_{u_R} + \text{h.c.}$$

$\Rightarrow \mathcal{G} = SO(5) \times U(1)_H$ is explicitely broken only by the SM

Constraints from EWSB

a two-scale problem

- electroweak scale $\langle h \rangle$ and the new physics scale set by the FN messenger mass m: $\langle h \rangle \ll m$

strategy

- match the Higgs potential within the SM, renormalized at the scale m, with the radiative potential in the full theory

spurion analysis

- main contribution from "top sector"

$$-\mathcal{L}_{\text{top}} = x \bar{\Psi}^3_{q_L} \Sigma \Psi^3_{u_R} + z_{\rm L} \bar{\Psi}^3_{q_L} \Sigma\, \xi_0 + z_{\rm R} \bar{\Psi}^3_{u_R} \Sigma\, \xi_1 + a_0 \bar{\xi}_1\, \Sigma \xi_0 + \text{h.c.}$$

Constraints from EWSB

SM (tree level + top)

$$V_{\text{SM}}^{(1)} = \frac{1}{4}\lambda(m)h^4 - \frac{1}{2}\mu^2(m)h^2 - \frac{N_c}{16\pi^2}m_t^4(h)\left(\log\frac{m_t^2(h)}{m^2} - \frac{3}{2}\right)$$

Axiflavon-Higgs ("top sector")

$$V_{\text{AFH}}^{(1)} = -\frac{N_c}{16\pi^2}\left\{m_t^4(h)\left(\log\frac{m_t^2(h)}{m^2} - \frac{3}{2}\right) + \sum_j m_{\xi_j}^4(h)\left(\log\frac{m_{\xi_j}^2(h)}{m^2} - \frac{3}{2}\right)\right\}$$

field-dependent FN masses: $m_{\xi_j}^2(h) = m^2 + f_j(h)$

Constraints from EWSB

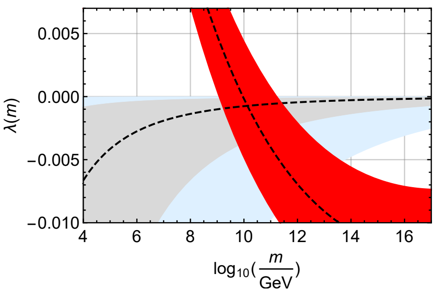
fine tuning is required for the quadratic $\mu^2(m)h^2$

$$\mu^2(m) = -\frac{N_c f^2}{16\pi^2}\left(x^2\left(z_{\rm L}^2 + z_{\rm R}^2\right) - 2\,x\,z_{\rm L}\,z_{\rm R}\,a_0\,\cos\,\Omega\right) + \mathcal{O}(f^2/2m^2)$$

after tuning, strong prediction for the quartic $\lambda(m)h^4$

$$\lambda(m) = -\frac{N_c}{4\pi^2}\frac{f^2}{2m^2}x^4(z_{\rm L}^2 + z_{\rm R}^2) + \mathcal{O}(f^2/2m^2) < 0.$$

Constraints from EWSB



- average Yukawa given by $y_t(m)(1+\delta)$
- matching is possible for ($f_a \sim f/50$): $10^7\,\text{GeV} \lesssim f_a \lesssim 10^{12}\,\text{GeV}$
- constraint from $K^+ \to \pi^+ + a$: $f_a \approx (10^{11} - 10^{12})\,\text{GeV}$

Constraints from EWSB

including right-handed neutrinos:

- Ψ_N as $SO(5)$ spurion **4**:

$$-\mathcal{L}_N = \frac{1}{\sqrt{2}} y_N \bar{\Psi}_N \Sigma' \mathcal{C} \bar{\Psi}_N^T + \text{h.c.}$$

- Majorana mass:

$$m_{N_{\mathrm{R}}}^2(h) = y_N^2 f^2 \cos^2(h/f)$$

- light neutrino mass (double suppression):

$$m_\nu \sim m_t \left(\frac{f^2}{2m^2}\right)^{|\delta_\nu|-1} \frac{m_t}{m_{N_{\mathrm{R}}}}$$

Constraints from EWSB

matching:

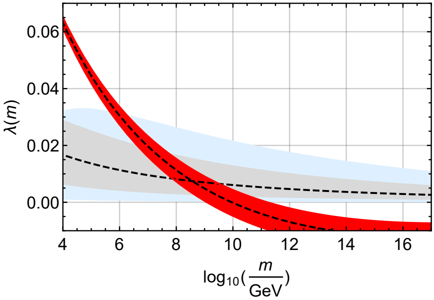
- tuning between RH-νs and top contributions

$$\mu^2(m) = \frac{f^2}{16\pi^2}\left[2y_N^4\left(1 + 2\log\frac{m}{y_N f}\right) - N_c\gamma_0\right]$$

- leading quartic from RH-νs

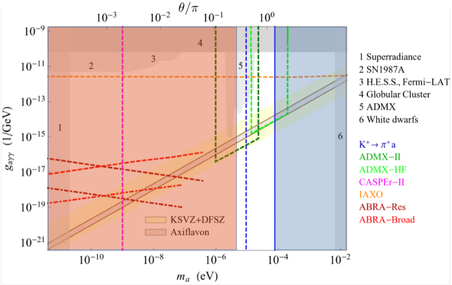
$$\lambda(m) = \frac{1}{4\pi^2}\log\frac{m}{y_N f}\, y_N^4 > 0$$

Constraints from EWSB



- matching is possible for 6 TeV $\lesssim f_a \lesssim 2 \times 10^6$ TeV
- a heavy axion can avoid Kaon-decay and SN-cooling constraints
- how? m_a and f_a can be disentangled [1604.01127], no axion-DM, still solving the strong CP problem

Conclusion



- framework to address flavor hierarchies with elementary pNGB-Higgs
- axiflavon-Higgs unification constrains the axion decay constant by the requirement of successful EWSB
- once the Higgs mass is tuned, the quartic coupling is predicted: f_a is tied to a very narrow range 10^{11}-10^{12} GeV
- including right-handed neutrinos, f_a can be lowered down to $\mathcal{O}(10)$ TeV (extra model-building needed)