

A common source for scalars: Axiflavor-Higgs unification

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Flavor and Dark Matter 2018
Karlsruhe, 24th September



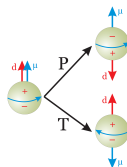
Outlook

- 1 motivation
- 2 the axiflavor
- 3 the axiflavor-Higgs
- 4 constraints from EWSB
- 5 large N_f Yukawa
- 6 conclusion

Motivation

many puzzles in the SM:

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



LEPTONS			Masses in MeV
Electron Neutrino Mass: 0	Muon Neutrino Mass: 0	Tau Neutrino Mass: 0	
Electron Mass: 0.511	Muon Mass: 105.7	Tau Mass: 1777	
QUARKS			Masses in MeV
Up Mass: 2.2	Down Mass: 4.7	Strange Mass: 96	
Charm Mass: 1270	Bottom Mass: 4180	Top Mass: 173200	

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

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](#)]

Axiflavor setup

symmetries

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

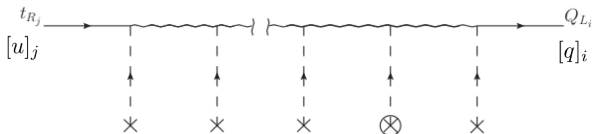
matter content

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

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

FN mechanism for mass generation

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



- in the IR, effective operators look like (up quarks)

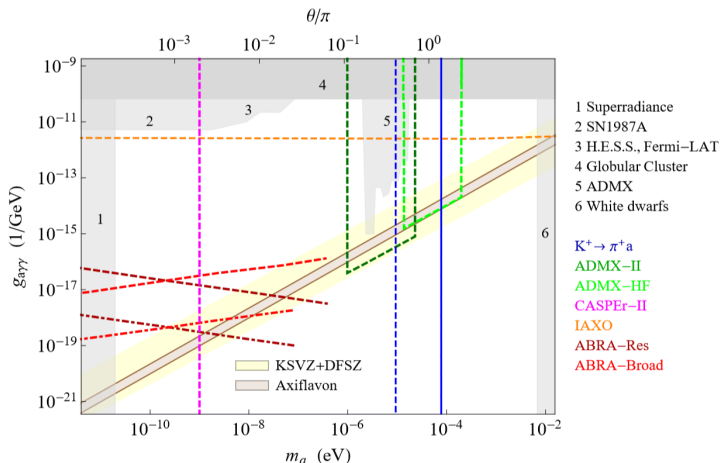
$$\mathcal{O} = \bar{q} \left(\frac{\Phi}{\Lambda} \right)^{[q]-[u]} \tilde{h} u \rightarrow m \sim v_h \left(\frac{f}{\Lambda} \right)^{[q]-[u]}$$

- CKM matrix

$$V_{\text{CKM}ij} \sim \left(\frac{f}{\Lambda} \right)^{[q]_j - [q]_i} \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

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 a non trivial Φ - h interplay?
 - theoretically appealing to unify all the scalars degrees of freedom in the theory
 - FN mechanism: $v_H \ll f \rightarrow$ suggests to realize the Higgs as pNGB
-
- flavor story for elementary Goldstone-Higgs models

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

symmetries

- $\mathcal{G} = SO(5) \times U(1)_H \rightarrow SO(4) = \mathcal{H}$
- \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} ,

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

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

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

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

fermions

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

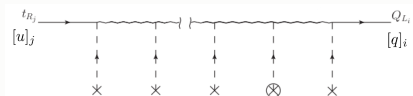
$$-\mathcal{L} \supset \sum_j (\bar{\xi}_{j+1} \Gamma^\alpha \Sigma_\alpha \xi_j + \text{h.c.}) + m_j \bar{\xi}_j \xi_j$$

- SM fermions as $\mathbf{4}$ spurions Ψ_f^i :

$$\begin{aligned} -\mathcal{L} \supset & \sum_{i,f} \bar{\Psi}_f^i \Gamma^\alpha \Sigma_\alpha \xi_j + \bar{\xi}_{j+2} \Gamma^\alpha \Sigma_\alpha \Psi_f^i \\ & + \bar{\Psi}_{qL}^3 \Gamma^\alpha \Sigma_\alpha \Psi_{uR}^3 + \text{h.c.} \end{aligned}$$

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

Integrating out



all yukawas are $\mathcal{O}(1)$: hierarchies controlled by charge difference n_{ij} ,

$$\frac{m_{ij}}{m_t} \sim \left(\frac{f^2}{2m^2} \right)^{n_{ij}}, \quad \frac{f^2}{2m^2} = \sin\theta_C \sim 0.23$$

example: up-quark charges leading to a viable spectrum:

$$n_{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}$$

Constraints from EWSB

a two-scale problem

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

strategy

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

spurion analysis

- main contribution from “top sector”

$$-\mathcal{L}_{\text{top}} = x \bar{\Psi}_{qL}^3 \Sigma \Psi_{uR}^3 + z_L \bar{\Psi}_{qL}^3 \Sigma \xi_0 + z_R \bar{\Psi}_{uR}^3 \Sigma \xi_1 + a_0 \bar{\xi}_1 \Sigma \xi_0 + \text{h.c.}$$

Constraints from EWSB

SM (tree level + top)

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

Axiflavor-Higgs (“top sector”)

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

Constraints from EWSB

$$V_{\text{SM}}^{(1)} = V_{\text{AFH}}^{(1)},$$

$$\Rightarrow \frac{1}{4}\lambda(m)h^4 - \frac{1}{2}\mu^2(m)h^2 = -\frac{N_c}{16\pi^2} \sum_j m_{\xi_j}^4(h) \left(\log \frac{m_{\xi_j}^2(h)}{m^2} - \frac{3}{2} \right)$$

large logarithm $\log \frac{m_{\xi_j}^2(h)}{m^2}$ cancels, expansion in $f^2/2m^2$

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

$$\text{RHS} = -\frac{N_c}{16\pi^2} \sum_j \left[-2f_j(h)m^2 + \frac{f_j^3(h)}{3m^2} - \frac{f_j^4(h)}{12m^4} + \frac{f_j^5(h)}{30m^6} - \frac{f_j^6(h)}{60m^8} + \mathcal{O}(f^2/2m^2) \right]$$

Constraints from EWSB

- RHS can be computed recursively:

$$F_1 = \sum_j f_j(h) = \text{Tr} [m^\dagger(h)m(h)] - m_t^2(h),$$

$$F_2 = \sum_j f_j^2(h) = \text{Tr} [(m^\dagger(h)m(h))^2] - 2F_1 m^2 - m_t^4(h)$$

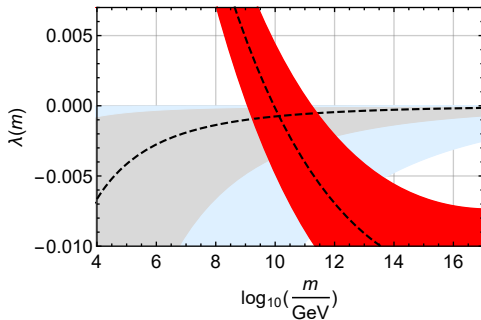
- $m_t^2(h)$ by solving perturbatively $\mathcal{P}(m_t(h)) = 0$
- fine tuning is required for the quadratic

$$\mu^2(m) = -\frac{N_c f^2}{16\pi^2} (x^2 (z_L^2 + z_R^2) - 2 x z_L z_R a_0 \cos \Omega) + \mathcal{O}(f^2/2m^2)$$

- after tuning, strong prediction for the quartic

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

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 $K^+ \rightarrow \pi^+ + a$:

$$f_a \approx (10^{11} - 10^{12}) \text{ GeV}$$

Constraints from EWSB

including right-handed neutrinos:

- Ψ_N as $SO(5)$ spurion **4**:

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

- Majorana mass:

$$m_{N_R}^2(h) = y_N^2 f^2 \cos^2(h/f)$$

- light neutrino mass (double suppression):

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

Constraints from EWSB

matching

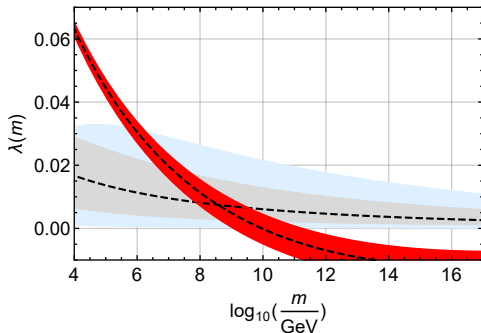
- tuning between RH- ν s and top contributions

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

- leading quartic from RH- ν s

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

Constraints from EWSB



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

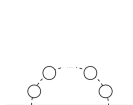
Large N_f Yukawa

- resummation techniques large for a large number of flavors N_f (for QED see: A. Palanques-Mestre, P. Pascual. Z.Phys C13, 1982)
- $1/N_f$ expansion relevant for asymptotic safety
- gap in the literature regarding large N_f interacting via Yukawa interaction:

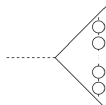
$$\mathcal{L}_{\text{Yuk}} = g\bar{\psi}\psi\phi, \quad K = \frac{g^2}{4\pi^2} N_f$$



(a) Scalar self-energy corrections.

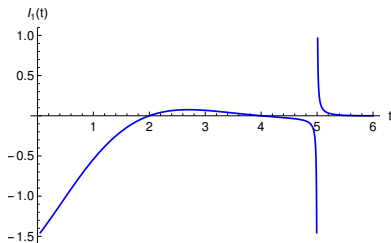


(b) Fermion self-energy correction.



(c) Vertex correction.

Large N_f Yukawa



- the β -function is [1806.06954]:

$$\frac{\beta(K)}{K^2} = 1 + \frac{1}{N_f} \left\{ \frac{3}{2} + \int_0^K h_1(t) dt \right\} + \mathcal{O}(1/N_f^2)$$

- extended to abelian gauge-Yukawa system in [1808.03252]

Conclusion

- axiflavor-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)
- framework to address flavor hierarchies in an elementary pNGB-Higgs picture
- large N_f technique for model-building