Flavor puzzle and the Goldstone-Higgs

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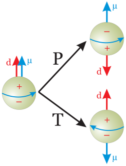
Outlook

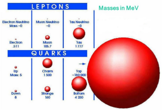
1. motivation
2. the axiflavon
3. the axiflavon-Higgs
4. constraints from EWSB
5. large N_f Yukawa

Motivation

many puzzles in the SM:

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





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

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

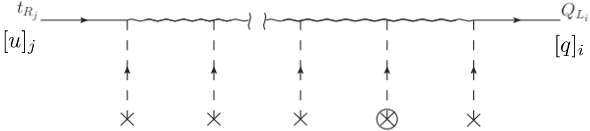
matter content

- 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 (up quarks)

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

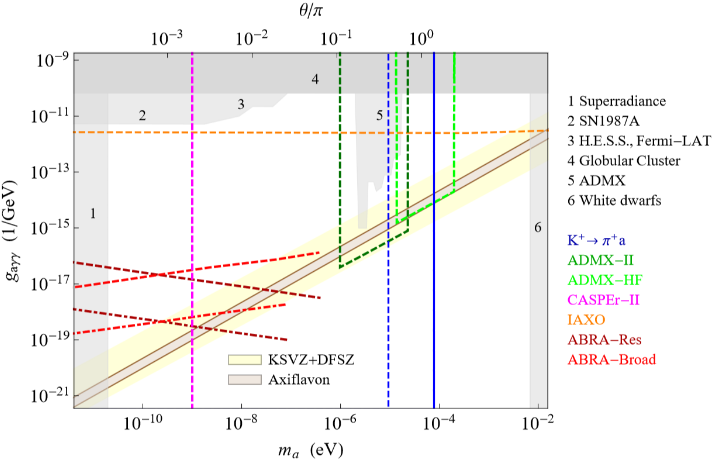
- CKM matrix

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

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

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 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

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

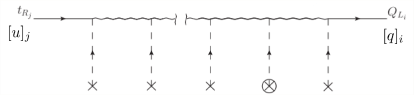
$$-\mathcal{L} \supset \sum_j \left(\bar{\xi}_{j+1}\, \Gamma^\alpha\, \Sigma_\alpha\, \xi_j + \text{h.c.}\right) + m_j\, \bar{\xi}_j\, \xi_j$$

- 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

Integrating out



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

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

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"

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

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")

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

Constraints from EWSB

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

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

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

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

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

Constraints from EWSB

- RHS can be computed recursively:

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

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

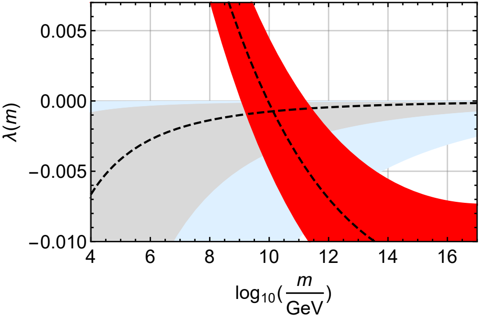
- $m_t^2(h)$ by solving perturbatively $\mathcal{P}(m_t(h)) = 0$
- fine tuning is required for the quadratic

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

- after tuning, strong prediction for the quartic

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

Constraints from EWSB



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

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

Constraints from EWSB

including right-handed neutrinos:

- Ψ_N as $SO(5)$ spurion $\mathbf{4}$:

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

- 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

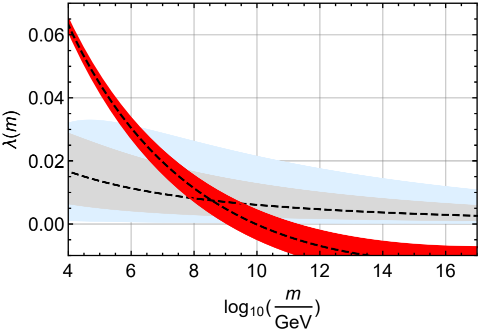
- tuning between RH-νs and top contributions

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

- 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 K-decay and SN-cooling constraints
- how? disentangling m_a and f_a [1604.01127]
- not DM anymore, but still solves strong CP

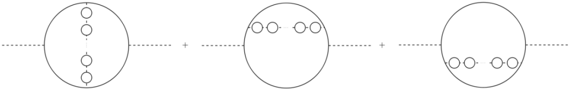
Conclusion 1

- 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)
- framework to address flavor hierarchies in an elementary pNGB-Higgs picture

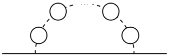
Large N_f Yukawa

- $1/N_f$ proven to be relevant for asymptotic safety
- gap in the literature regarding large N_f interacting via Yukawa interaction (tree level $\lambda = 0$):

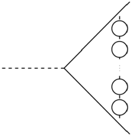
$$\mathcal{L}_{\text{Yuk}} = g\bar{\psi}\psi\phi, \qquad K = \frac{g^2}{4\pi^2}N_f$$



(a) Scalar self-energy corrections.

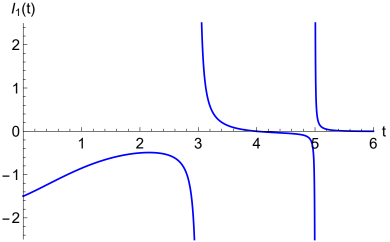


(b) Fermion self-energy correction.



(c) Vertex correction.

Large N_f Yukawa



- the β-function (checked up to 4-loop) is [1806.06954]:

$$\frac{\beta(K)}{K^2} = 1 + \frac{1}{N_f}\left\{\frac{3}{2} + \int_0^K I_1(t)\mathrm{d}t\right\} + \mathcal{O}(1/N_f^2)$$

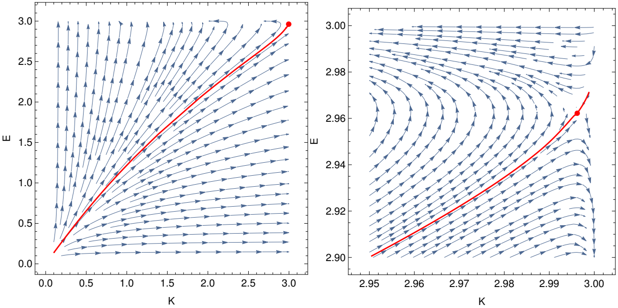
- radius of convergence: $K = 3$, same as non-abelian gauge theory

Large N_f Yukawa

- we extended the analysis to abelian gauge-Yukawa

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + i\bar{\psi}\not{D}\psi + y\bar{\psi}\psi\phi$$

- the coupled system of β-functions is computed in [1808.03252]



- singularities: $(K, E) = (3, 3), (3, 0), (0, 3?)$

Conclusion 2

- large N_f Yukawa proven to affect singularities
- we computed the $1/N_f$ β-function for pure Yukawa, singularity at $K = 3$ - like non-abelian gauge theory (does it mean anything?)
- extended to $1/N_f$ abelian gauge-Yukawa coupled system
- singularities at $(3, 3)$, $(3, 0)$, $(0, 3?)$