Renormalizable Models of Flavor-Specific Scalars

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Motivation

- New light scalar singlets feature prominently in SM extensions.
- For example, such scalars may be mediators to a dark sector.
- Apart from the Yukawa couplings, the new scalar-fermionic couplings in SM extensions tend to break the flavor symmetry.
- May lead to the dangerous prospect of new large FCNCs.
- A standard way to evade is via the MFV hypothesis, with new couplings $\propto Y_w Y_d$.
The flavor-specific hypothesis takes a different route by having couplings to only one flavor in the mass basis. This is a technically natural, radiatively stable hypothesis, similar to alignment.

EFT framework and its phenomenology was studied in depth in [1,2].

Here, we explore two UV completion scenarios: VLQ & Heavy Higgs-like scalar.

Focusing on an up-quark-specific model, we find that naturalness and experimental constraints in the UV theories are stronger than and complementary to those in the EFT[1,2].
Light scalar $S$ with flavor-specific couplings:

$$\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \left( \frac{c_S}{M} \overline{S} Q_L u_R H_c + \text{h.c.} \right)$$

In the up-specific hypothesis, the effective scalar up quark coupling is:

$$\mathcal{L}_S \supset -g_u S \overline{u} u, \quad g_u = \frac{c_S v}{\sqrt{2} M}$$

EFT has implications for the naturalness of the light singlet scalar, flavor violation, and CP violation.
Consider a new RH-up quark like $U'(3,1,\frac{2}{3})$ s.t.:

$$-\mathcal{L} \supset M \overline{U}'_L U'_R + y_i \overline{Q}'_L U'_R H_c + \lambda^i \overline{U}'_L u_{R_i} S + \text{h.c.}$$

Integrating out VLQ gives:

$$-\mathcal{L} \supset \frac{y_i \lambda^j}{M} S \overline{Q}'_L u_{R_j} H_c + \text{h.c.}$$

$$(c_S)^{ij}_i \equiv -y_i \lambda^j$$

After EWSB, there’s a mass mixing b/w $\{u, U'\}$ which can be diagonalized in the regime of $\{v_y u, \lambda vs\} \ll y v < M$ via:

$$u_L \rightarrow \cos \theta \ u_L + \sin \theta \ U'_L, \quad U'_L \rightarrow \cos \theta \ U'_L - \sin \theta \ u_L,$$

$$\cos \theta = \frac{M}{M_{U'}}, \quad \sin \theta = \frac{y v}{\sqrt{2} M_{U'}}.$$ 

where $M_{U'} = \sqrt{M^2 + (y v)^2}/2$ is the physical mass of VLQ.
VLQ : Decays

The decay widths for the VLQ are:

$$\Gamma(U' \rightarrow uS) = \cos^2 \theta \frac{\lambda^2 m_{U'}}{32 \pi} \left(1 - \frac{m_S^2}{m_{U'}^2}\right)^2 \approx \frac{\lambda^2 M}{32 \pi},$$

$$\Gamma(U' \rightarrow uh) = \sin^2 \theta \cos^2 \theta \frac{G_F m_{U'}^3}{16 \sqrt{2} \pi} \left(1 - \frac{m_h^2}{m_{U'}^2}\right)^2 \approx \frac{y^2 M}{64 \pi},$$

$$\Gamma(U' \rightarrow uZ) = \sin^2 \theta \cos^2 \theta \frac{G_F m_{U'}^3}{16 \sqrt{2} \pi} \left(1 - \frac{m_Z^2}{m_{U'}^2}\right)^2 \left(1 + \frac{2m_Z^2}{m_{U'}^2}\right) \approx \frac{y^2 M}{64 \pi},$$

$$\Gamma(U' \rightarrow dW) = \sin^2 \theta \frac{G_F m_{U'}^3}{8 \sqrt{2} \pi} \left(1 - \frac{m_W^2}{m_{U'}^2}\right)^2 \left(1 + \frac{2m_W^2}{m_{U'}^2}\right) \approx \frac{y^2 M}{32 \pi},$$

The decay width for light scalar $S$:

$$\Gamma(S \rightarrow u\bar{u}) = \sin^2 \theta \frac{\lambda^2 m_S}{8 \pi} \approx \frac{g_w^2 m_S}{8 \pi}.$$
VLQ : Naturalness

- Naturalness considerations: From radiative sizes of terms generated by S, H, up and U' interactions.

- Correction to scalar mass term at 1 loop:

  \[ \delta m_S^2 \sim \frac{\text{Tr} \, \lambda^* \lambda}{16\pi^2} M^2 \Rightarrow \lambda^i \lesssim 4\pi \frac{m_S}{M} \]

- Correction to Higgs mass at 1 loop:

  \[ \delta m_H^2 \sim \frac{\text{Tr} \, y y^*}{16\pi^2} M^2 \Rightarrow y_i \lesssim 4\pi \frac{v}{M} \]

- These two leads to an Naturalness bound on the EFT coupling:

  \[ g_u \lesssim \frac{16\pi^2}{\sqrt{2}} \frac{m_S v}{M^2} \approx (7 \times 10^{-4}) \left( \frac{m_S}{0.1 \text{GeV}} \right) \left( \frac{2 \text{TeV}}{M} \right)^2. \]
VLQ : CKM considerations

- There exists a tension between the SM theory and unitarity prediction for the top row CKM unitarity ("Cabbibo anomaly").

- Current experimental bounds gives[3] :

  \[ \left[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \right]_{\text{exp}} = 0.9985(3)V_{ud}(4)V_{us} \]

- Requiring theory prediction to be within 3 \( \sigma \) gives \( \sin \theta \leq 0.055 \), implying:

  \[ y \lesssim 0.6 \left( \frac{M}{2\,\text{TeV}} \right). \]
VLQ : FCNC bounds

- FCNC considerations come from the modification to Neutral Kaon mixing box diagrams:

\[ \mathcal{L} \supset C^{d\bar{s}} [\bar{d}_L \gamma^\mu s_L][\bar{d}_L \gamma^\mu s_L] + \text{h.c.}, \]

- We get,

\[ C^{d\bar{s}} = -y^4 |V^*_{ud} V_{us}|^2 / (128\pi^2 M^2). \]

- Current limits restrict:

\[ \text{Re}[C^{d\bar{s}}] \lesssim (10^3 \text{ TeV})^{-2} \]

- This can be translated as:

\[ y \lesssim 0.6 \left( \frac{M}{2 \text{ TeV}} \right)^{1/2}. \]
VLQ : EW Precision bounds

- Heavy VLQ modifies the partial width of $Z$, $R_\ell \equiv \frac{\Gamma[Z^{\rightarrow \text{had}}]}{\Gamma[Z^{\rightarrow \ell^+\ell^-}]}$.

  1. Tree-level shift through $u$-$U'$ mixing is dominant.
  2. Loops :

- Current data is $\delta R_\ell^{\text{exp}} = 0.034 \pm 0.025$ leading to $\frac{y_Y}{M} < 0.063$.
- Future data (FCC-ee) will give $\delta R_\ell^{\text{exp}} = 0.001$ leading to $\frac{y_Y}{M} < 0.022$. 
For complex $M, \gamma, \lambda$ large nEDM can arise from effective CPV 4-quark operator:

\[ \mathcal{L} \supset C_u' \bar{u}i\gamma^5 u \bar{u}, \quad C_u' = \frac{\text{Re}(Y_{\bar{s}uu})\text{Im}(Y_{s\bar{u}u})}{m_s^2} \approx -\frac{y^2 \lambda^2 v^2}{4M^2 m_s^2} \sin 2\phi_{\text{CP}} \]

Neutron EDM, in this terms gives, $d_n = 0.182 e C_u' \text{ GeV}$

Experimentally, we have $|d_n| < 1.8 \times 10^{-26} \text{ e cm}$, thus leading to:

\[ |g_u| \sqrt{\sin 2\phi_{\text{CP}}} < 3 \times 10^{-6} \left( \frac{m_s}{1 \text{ GeV}} \right) \]
We consider pair production of $U'$ and its decays $U' \to dW$. Assuming 20 fb$^{-1}$ at 8 TeV, the constraints is $M > 550 \text{ GeV}$. At 13 TeV with 300 fb$^{-1}$ luminosity, we get a constraint $M > 900 \text{ GeV}$. Analysis is close that done by CMS.
VLQ: Results (y vs M)
VLQ : Results (M=2 TeV) Visible Decay
VLQ : Results (M=2 TeV) Invisible Decay
Scalar Completion : Model

- We introduced a Higgs like scalar

\[ \mathcal{L}_{sd} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 + (D_\mu H')^\dagger D^\mu H' - M^2 H'^\dagger H' \\
- [y_{ij}^j \overline{Q}_L u_{Rj} H_c' + \kappa M S H'^\dagger H' + \text{h.c.}] + \text{quartic scalar couplings}, \]

- The effective dim-5 operator would be :

\[ \mathcal{L} \supset \frac{\kappa y_{ij}^j}{M} \overline{S} Q_L^i u_{Rj} H_c + \text{h.c.} \]
Scalar Completion: Results (y-M)
Conclusions

- Light dark sectors are a particularly interesting realm of contemporary BSM phenomenology with promising precision, beam dump, and direct detection experiments on the horizon.
- The up-specific models provides an interesting complementary benchmark to a Higgs-like scalars.
- Flavour-specific hypothesis can be applied easily to any of the quarks with minor modifications.
- UV completion of the previously studied EFT gives a wider picture and stronger constraints on the parameter space.
Appendix : Scalar completion( Model)

- We will rotate H, H’ to the Higgs basis:

\[
\hat{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1 + iG^0) \end{pmatrix}, \quad \hat{H}' = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2 + iA^0) \end{pmatrix}, \quad S = v_S + \phi_3,
\]

- The mixing angle is \( \tan \beta = \frac{v'}{v_0} \ll 1 \)

- Diagonalizing the mixed CP-even scalar fields \( \varphi_i \) will lead to mass eigenstates:

\[
R^T \mathcal{M}^2_\varphi R = \text{diag}\{m^2_h, m^2_{h'}, m^2_s\}.
\]

- The CP even scalar masses are:

\[
m^2_h \simeq 2\lambda v^2, \quad m^2_{h'} \simeq M^2, \quad m^2_s \simeq m^2_s - \kappa^2 v^2.
\]
Appendix : Scalar Model

- The charged Goldstones $A^0$ and $H^+$ are approx. degenerate:

$$m_{A^0,H^±}^2 = M^2 \cos^2{β} + (\mu'^2 - \kappa M v_s) \sin(2β) - \mu^2 \sin^4{β} \approx M^2$$

- The leading decays of heavier scalar are:

$$\Gamma(h' \to wū) = \Gamma(A^0 \to wū) = \Gamma(H^+ \to ud) \approx \frac{3y'^2 M}{16π},$$
$$\Gamma(h' \to sh) = \Gamma(A^0 \to sZ) = \Gamma(H^+ \to sW^+) \approx \frac{\kappa^2 M}{16π}.$$ 

- The decay for light scalar goes via:

$$\Gamma(s \to wū) \approx \frac{\kappa^2 y'^2 v^2 m_s}{16π M^2} = \frac{g_u^2 m_s}{8π}.$$
Scalar Phenomenology

- **FCNC considerations:**

\[ y \lesssim 0.6 \left( \frac{M}{2 \text{TeV}} \right)^{1/2} \]

- **Naturalness considerations:**

\[ |\kappa| \lesssim 4\pi \frac{m_s}{M} \]

- **Electroweak precision bounds:** Fixing \( M = 1 \text{ TeV}, m_s = 1 \text{ GeV}, \)

\[ R_l^{\text{exp}} - R_l^{\text{SM}} = 0.83 \ (y' = \kappa = \sqrt{4\pi}), \text{ excluded by current data} \ (\delta R_l = 0.034 \pm 0.025) \]

\[ R_l^{\text{exp}} - R_l^{\text{SM}} = 5.5 \times 10^{-3} \ (y' = \kappa = 1), \text{ FCC-ee : expected } \delta R_l = 0.001. \]
Scalar Completion : Results (M=2 TeV)
Scalar Completion: Results
References

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3. P. A. Zyla et al. (Particle Data Group), PTEP 2020, 083C01 (2020).