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 \( \propto Y_w Y_d \)
Motivation

- 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].
EFT Review

- Light scalar $S$ with flavor-specific couplings:

\[
\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \left( \frac{c_S}{M} S \bar{Q}_L u_R H_c + \text{h.c.} \right)
\]

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

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

- 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.:

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

Integrating out VLQ gives:

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

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

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

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

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:

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

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

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

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

The decay width for light scalar S:

\[ \Gamma(S \to u\bar{u}) = \sin^2 \theta \frac{\lambda^2 m_S}{8\pi} \approx \frac{g_w^2 m_S}{8\pi}. \]
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:

\[
g_u \lesssim \frac{16\pi^2}{\sqrt{2}} \frac{m_S v}{M^2} \approx (7 \times 10^{-4}) \left( \frac{m_S}{0.1 \text{GeV}} \right) \left( \frac{2 \text{TeV}}{M} \right)^2.
\]
There exists a tension between the SM theory and unitarity prediction for the top row CKM unitarity ("Cabbibo anomaly").

Current experimental bounds give[3] :

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

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:

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

- We get,

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

- Current limits restrict:

\[ \text{Re}[C^{ds}] \lesssim (10^3 \text{ TeV})^{-2}. \]

- 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:

    ![Diagram](image)

- Current data is $\delta R_\ell^{\text{exp}} = 0.034 \pm 0.025$ leading to $\frac{\gamma\gamma}{M} < 0.063$.
- Future data (FCC-ee) will give $\delta R_\ell^{\text{exp}} = 0.001$ leading to $\frac{\gamma\gamma}{M} < 0.022$. 
 VLQ: EDM bounds

- For complex $M, \gamma \& \lambda$, large nEDM can arise from effective CPV 4-quark operator:

$$\mathcal{L} \supset C'_u \bar{u}i\gamma^5 u \bar{u}u,$$

$$C'_u = \frac{\text{Re}(Y_{S\bar{u}u}) \text{Im}(Y_{S\bar{u}u})}{m_S^2} \approx -\frac{y^2 \lambda^2 v^2}{4M^2 m_S^2} \sin 2\phi_{\text{CP}}$$

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

- Experimentally, we have $|d_n| < 1.8 \times 10^{-26} \, e \, \text{cm}$, 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 $U' \rightarrow dW$. Assuming 20 fb$^{-1}$ at 8 TeV, the constraints is $M > 550$ GeV. At 13 TeV with 300 fb$^{-1}$ luminosity, we get a constraint $M > 900$ 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
We introduced a Higgs like scalar

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

The effective dim-5 operator would be:

\[ \mathcal{L} \supset \frac{\kappa}{M} y_{i}^{ij} \overline{Q}_L^i u_{Rj} H_c + \text{h.c.} \]
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 \(\phi_i\) will lead to mass eigenstates:

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

- 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:

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

- The leading decays of heavier scalar are:

$$\Gamma(h' \to u\bar{u}) = \Gamma(A^0 \to u\bar{u}) = \Gamma(H^+ \to u\bar{d}) \approx \frac{3 y'^2 M}{16 \pi}$$

$$\Gamma(h' \to s\bar{h}) = \Gamma(A^0 \to sZ) = \Gamma(H^+ \to sW^+) \approx \frac{\kappa^2 M}{16 \pi}.$$ 

- The decay for light scalar goes via:

$$\Gamma(s \to u\bar{u}) \approx \frac{\kappa^2 y'^2 v^2 m_s}{16 \pi M^2} = \frac{g_u^2 m_s}{8 \pi}.$$
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 \( M = 1 \text{TeV}, m_S = 1 \text{GeV}, \)
  - \( R_l^{\text{exp}} - R_l^{\text{SM}} = 0.83 (y' = \kappa = \sqrt{4\pi}), \) excluded by current data\( (\delta R_l = 0.034 \pm 0.025) \)
  - \( R_l^{\text{exp}} - R_l^{\text{SM}} = 5.5 \times 10^{-3} (y' = \kappa = 1), \) FCC-ee: expected \( \delta R_l = 0.001. \)
Scalar Completion : Results (M=2 TeV)
Scalar Completion : Results
References

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