

Renormalizable Models of Flavor-Specific Scalars

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[arXiv:2107.08059](https://arxiv.org/abs/2107.08059) [**hep-ph**]



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 $\propto Y_u, Y_d$.



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[1,2].

VLQ completion : Model

- Consider a new RH-up quark like $U'(3,1,\frac{2}{3})$ s.t. :

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

- Integrating out VLQ gives :

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

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

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

$$\begin{aligned} u_L &\rightarrow \cos \theta u_L + \sin \theta U'_L, & U'_L &\rightarrow \cos \theta U'_L - \sin \theta u_L, \\ \cos \theta &= \frac{M}{M_{U'}}, & \sin \theta &= \frac{yv}{\sqrt{2} M_{U'}}. \end{aligned}$$

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

VLQ : Decays

- The decay widths for the VLQ are :

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

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

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

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

- The decay width for light scalar S :

$$\Gamma(S \rightarrow u\bar{u}) = \sin^2\theta \frac{\lambda^2 m_S}{8\pi} \simeq \frac{g_u^2 m_S}{8\pi}.$$

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 :

$$\delta m_H^2 \sim \frac{\text{Tr } yy^*}{16\pi^2} M^2 \Rightarrow y_i \lesssim 4\pi \frac{v}{M}$$

- ▶ 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] :

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

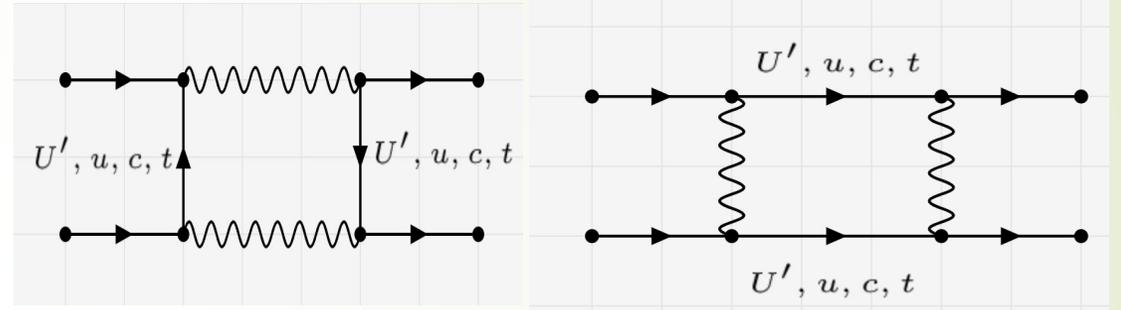
- ▶ Requiring theory prediction to be within 3σ gives $\sin\theta \lesssim 0.055$, implying:

$$y \lesssim 0.6 \left(\frac{M}{2\text{TeV}} \right).$$

VLQ : FCNC bounds

- FCNC considerations comes 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 : $\text{Re}[C^{ds}] \lesssim (10^3 \text{ TeV})^{-2}$

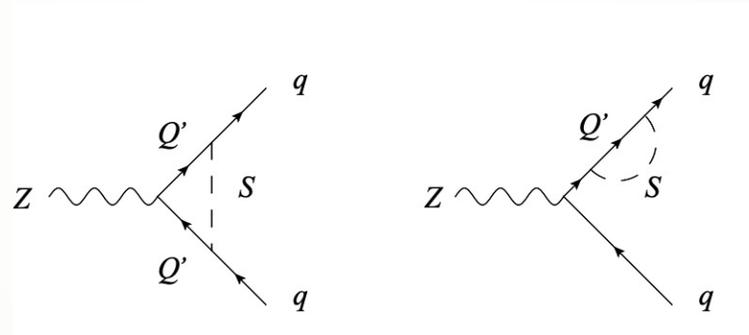
- This can be translated as :

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

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 :



- Current data(LEP) is $\delta R_\ell^{exp} = 0.034 \pm 0.025$ leading to $\frac{y v}{M} < 0.063$.
- Future data(FCC-ee) will give $\delta R_\ell^{exp} = 0.001$ leading to $\frac{y v}{M} < 0.022$.

VLQ: EDM bounds

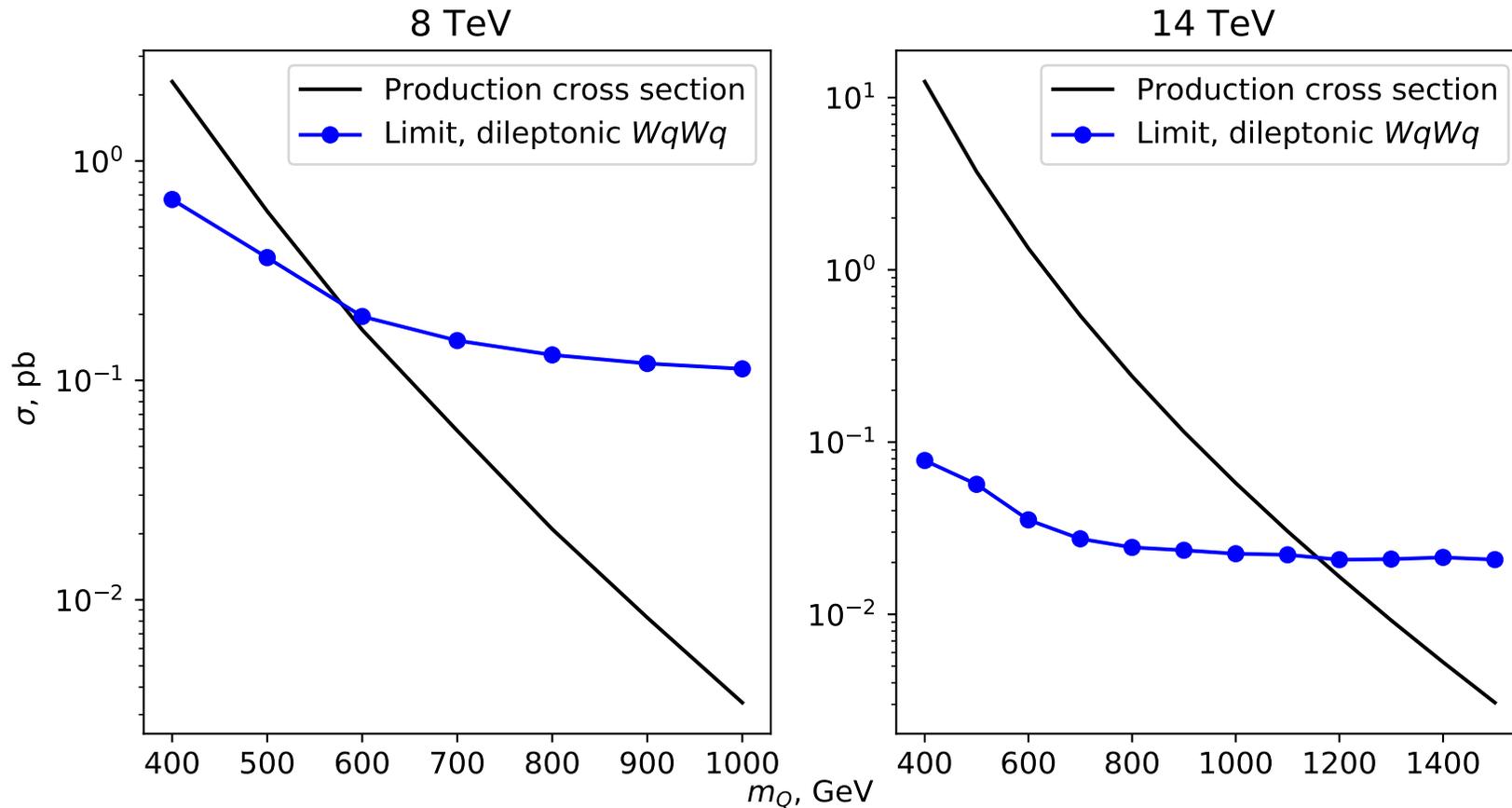
- For complex M, y & λ , large nEDM can arise from effective CPV 4-quark operator :

$$\mathcal{L} \supset C'_u \bar{u} i \gamma^5 u \bar{u} u, \quad C'_u = \frac{\text{Re}(Y_{S\bar{u}u}) \text{Im}(Y_{S\bar{u}u})}{m_S^2} \simeq -\frac{y^2 \lambda^2 v^2}{4M^2 m_S^2} \sin 2\phi_{\text{CP}}$$

- 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 :

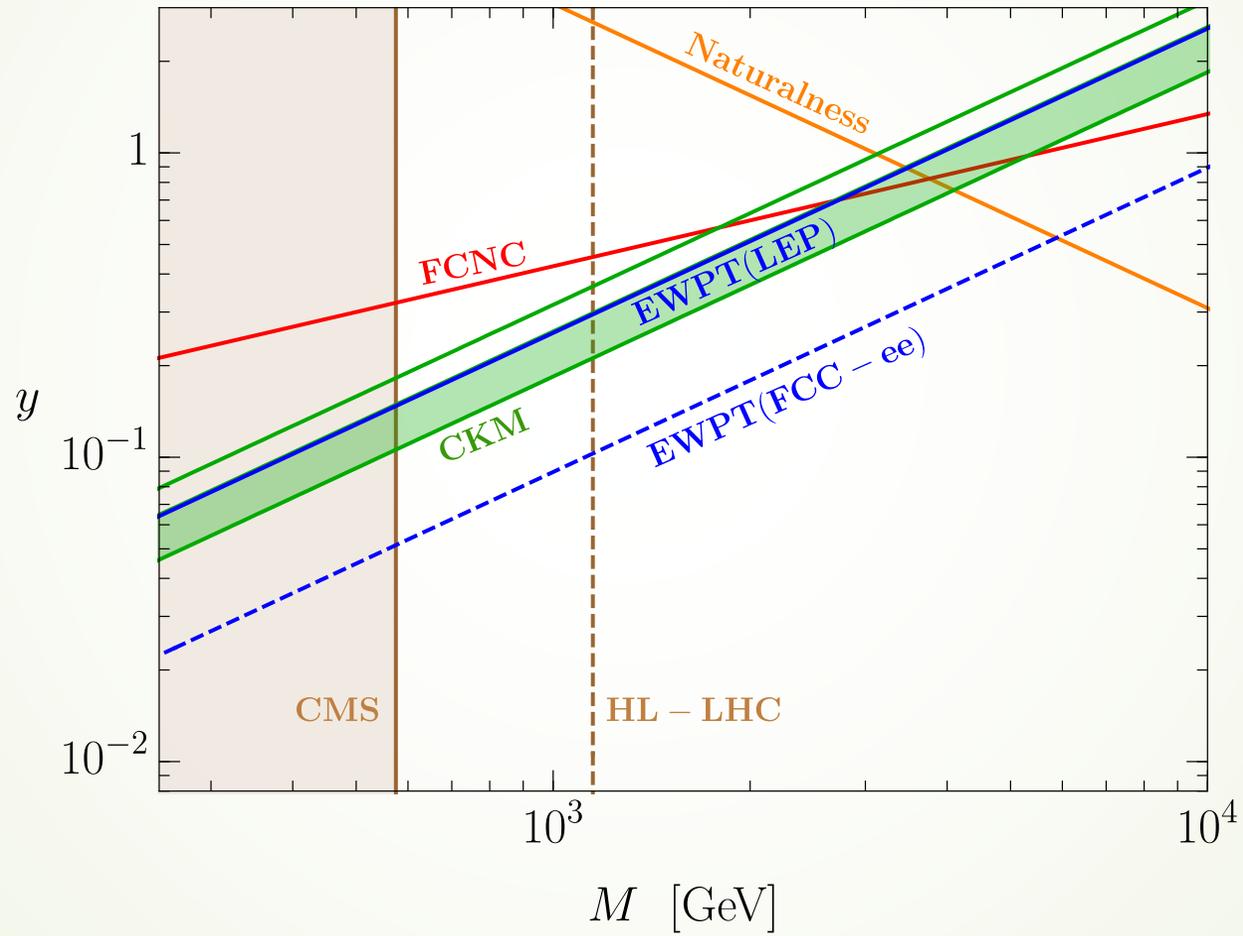
$$|g_u| \sqrt{\sin 2\phi_{\text{CP}}} < 3 \times 10^{-6} \left(\frac{m_S}{1 \text{ GeV}} \right)$$

VLQ : Collider Phenomenology

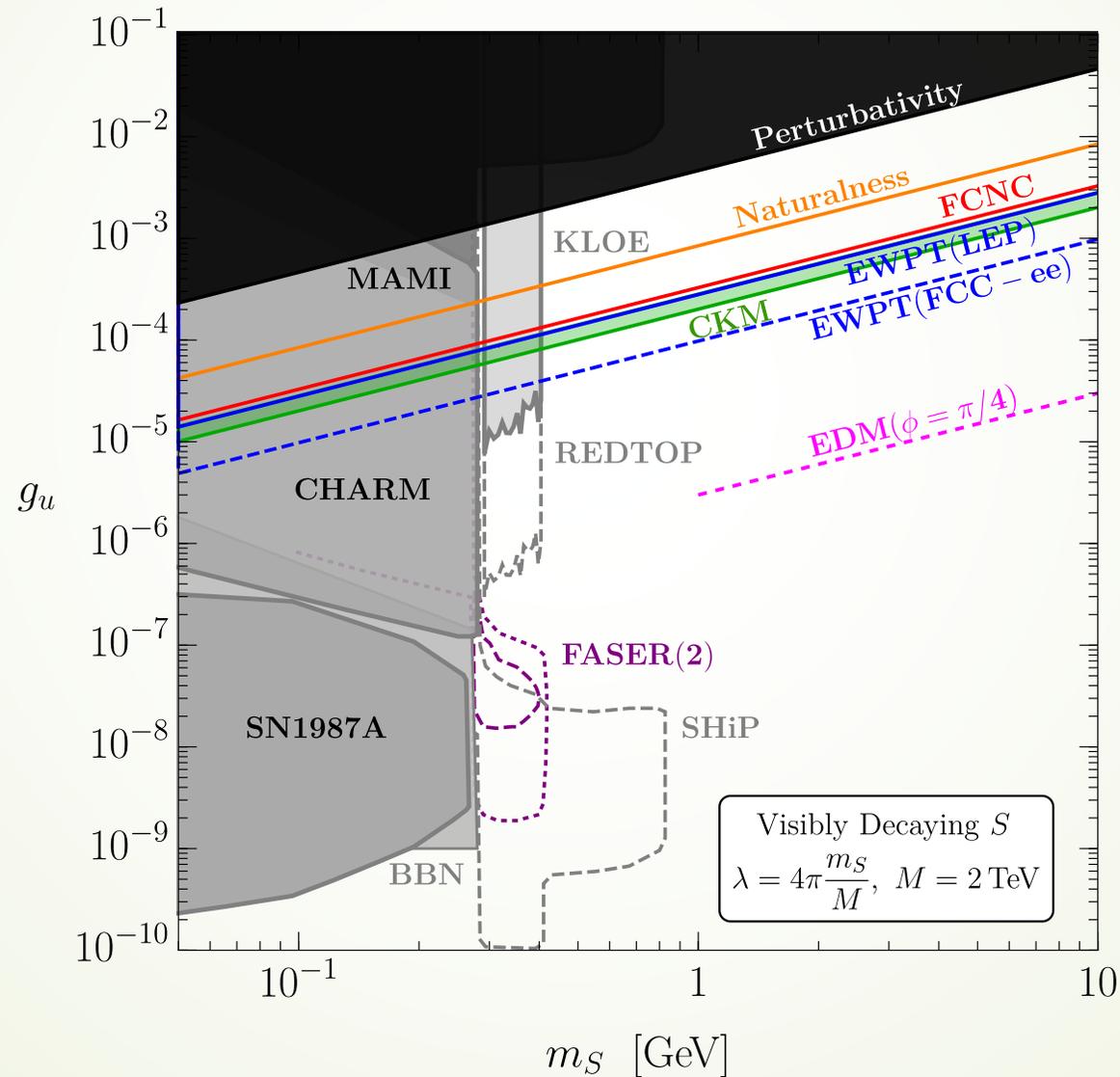


We consider pair production of U' and its decays $U' \rightarrow dW$. Assuming 20 fb^{-1} at 8 TeV , the constraints is $M > 575 \text{ GeV}$. At 14 TeV with 3000 fb^{-1} luminosity, we get a constraint $M > 1150 \text{ GeV}$. Analysis is close to that done by CMS.

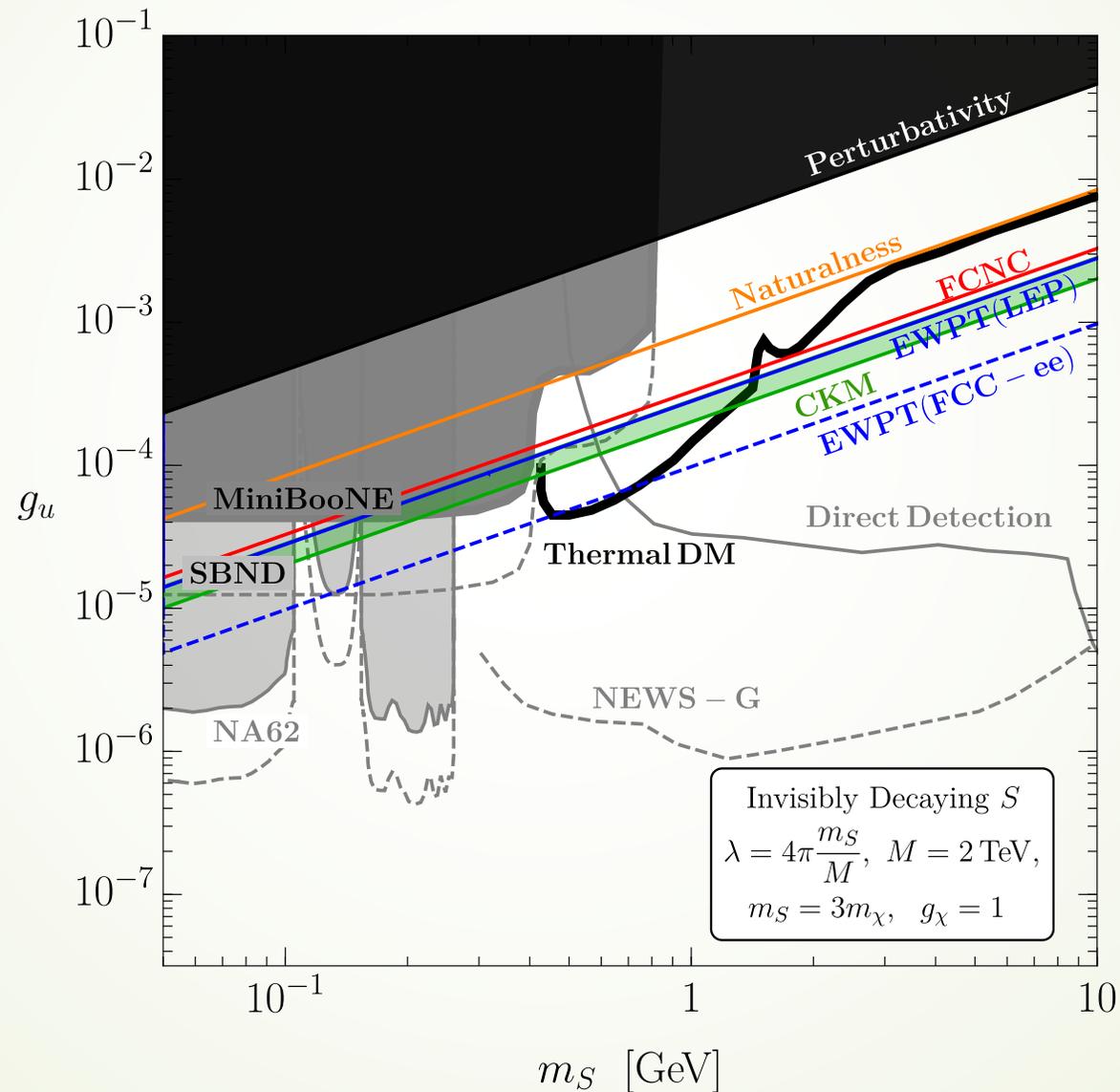
VLQ: Results (y vs M)



VLQ : Results (Visible Decay)



VLQ : Results (Invisible Decay)



Scalar Completion : Model

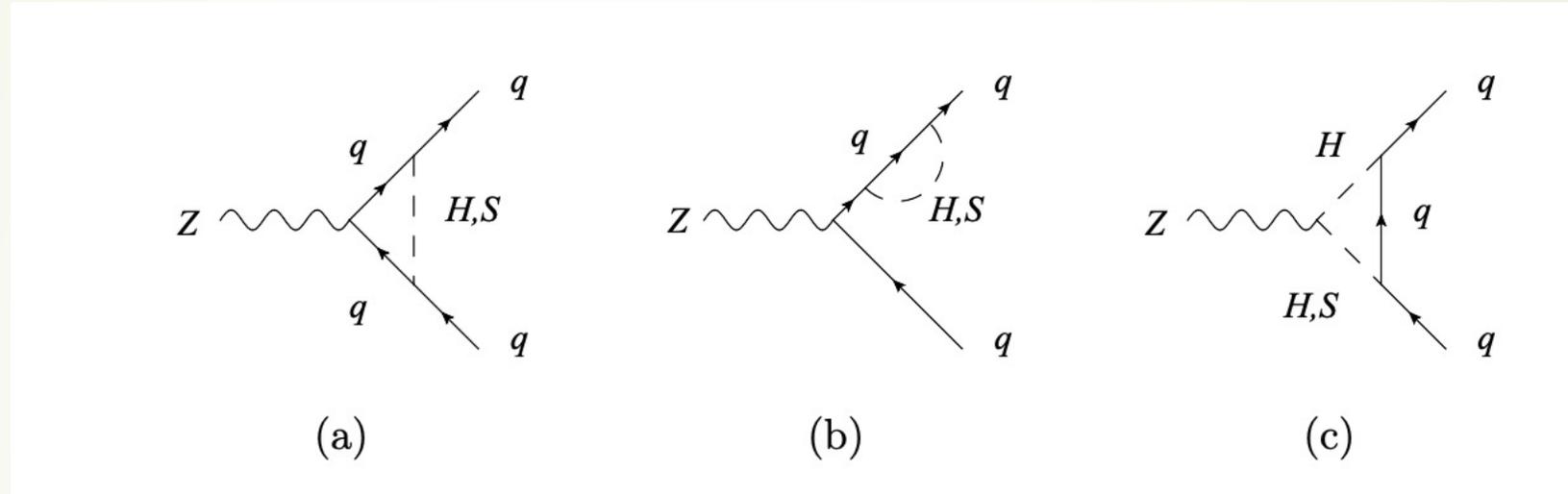
- We introduced a Higgs like scalar

$$\begin{aligned}\mathcal{L}_{\text{sd}} = & \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 + (D_\mu H')^\dagger D^\mu H' - M^2 H'^\dagger H' \\ & - [y'^j_i \overline{Q}_L^i u_{Rj} H'_c + \kappa M S H'^\dagger H' + \text{h.c.}] + \text{quartic scalar couplings,}\end{aligned}$$

- The effective dim-5 operator would be :

$$\mathcal{L} \supset \frac{\kappa y'^j_i}{M} S \overline{Q}_L^i u_{Rj} H'_c + \text{h.c.}$$

Scalar Phenomenology



- EW precision bounds : Fixing $M = 1 \text{ TeV}, m_s = 1 \text{ GeV}$,
 - $R_l^{exp} - R_l^{SM} = 0.83$ ($y' = \kappa = \sqrt{4\pi}$), excluded by current data ($\delta R_l = 0.034 \pm 0.025$)
 - $R_l^{exp} - R_l^{SM} = 5.5 \times 10^{-3}$ ($y' = \kappa = 1$), FCC-ee : expected $\delta R_l = 0.001$.

Scalar Phenomenology

- Naturalness considerations :

$$|\kappa| \lesssim 4\pi \frac{m_S}{M}$$

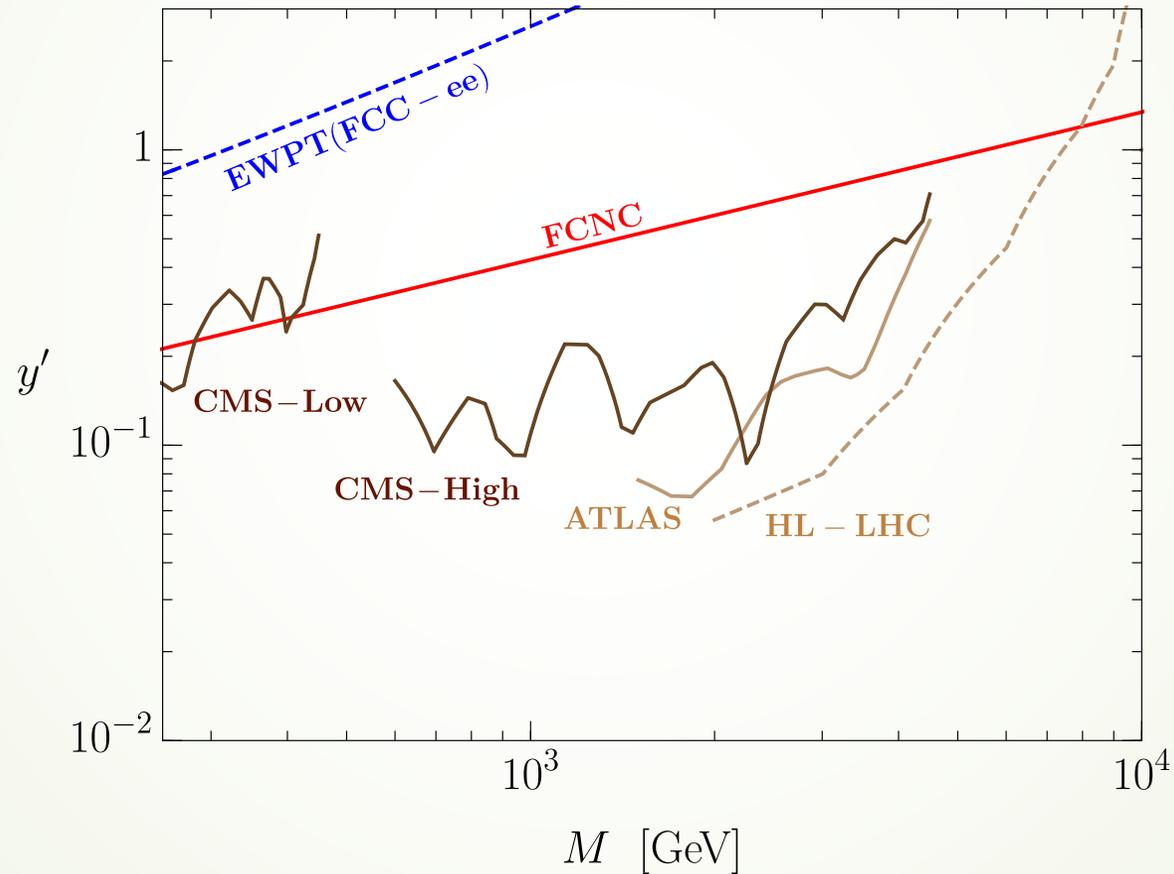
- FCNC considerations :

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

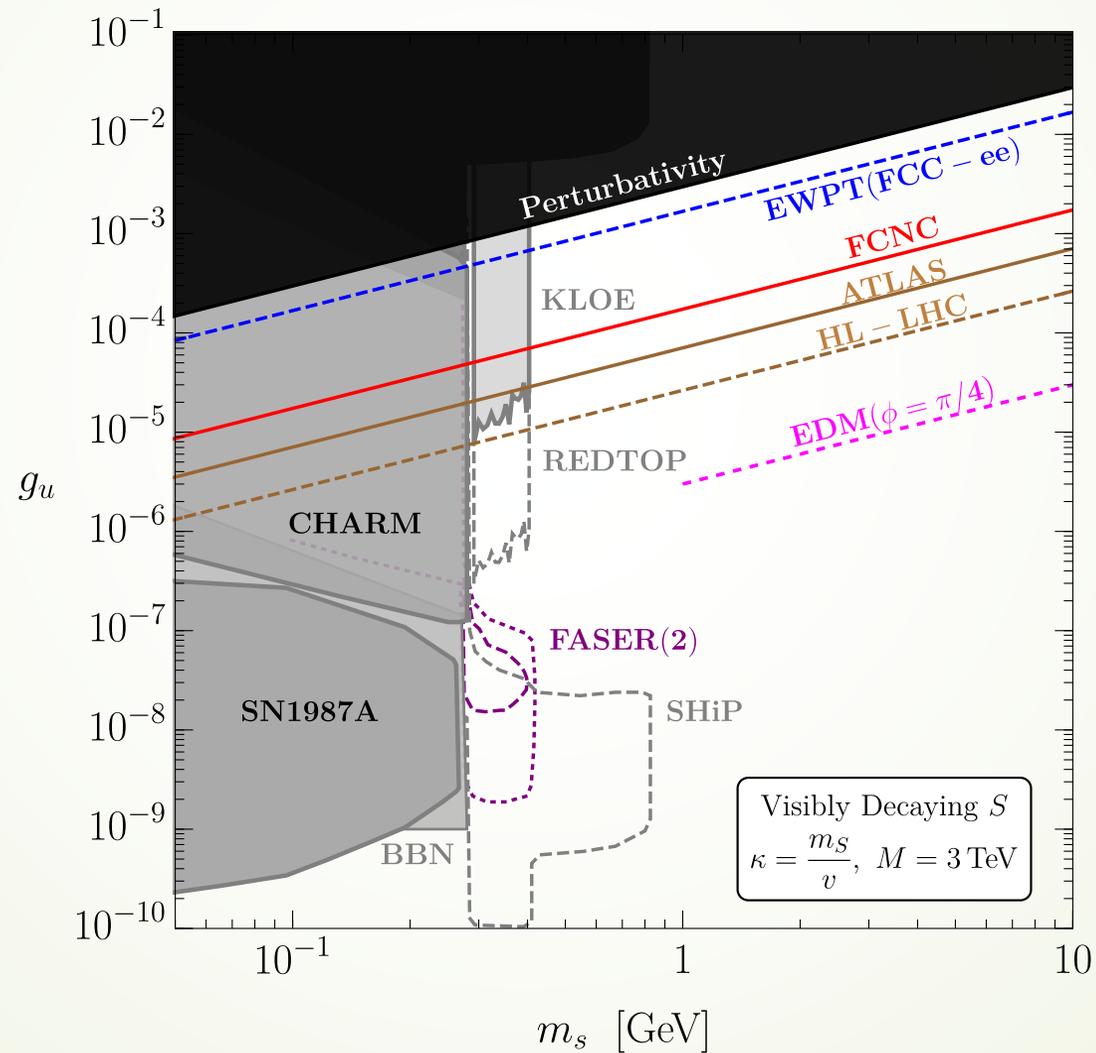
- CP Violation:

$$|g_u| \sqrt{\sin 2\phi_{\text{CP}}} < 3 \times 10^{-6} \left(\frac{m_S}{1 \text{ GeV}} \right)$$

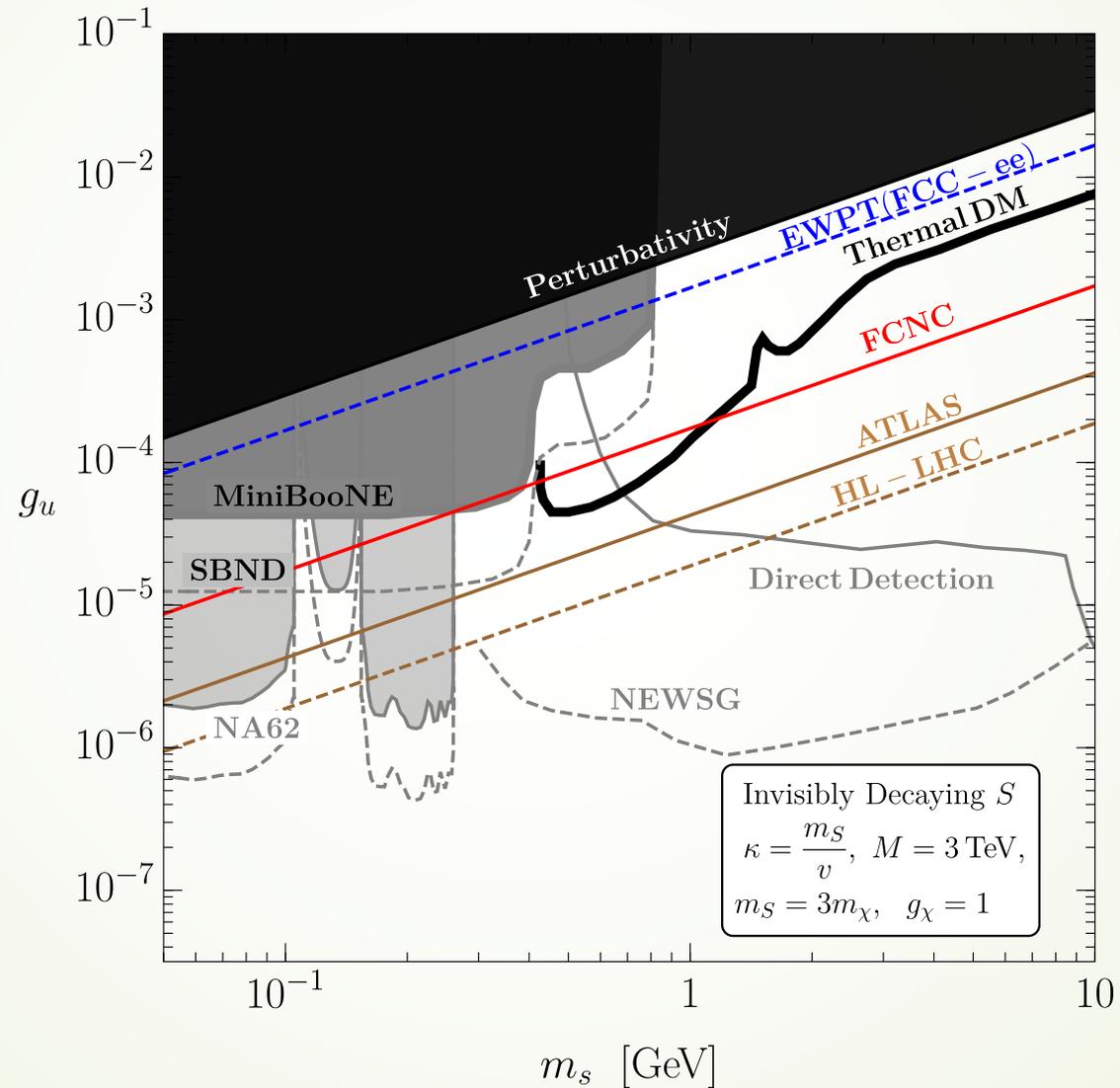
Scalar Completion: Results (y - M)



Scalar Completion :Results



Scalar Completion :Results





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 φ_i will lead to mass eigenstates:

$$R^T \mathcal{M}_\phi^2 R = \text{diag}\{m_h^2, m_{h'}^2, m_s^2\};$$

- The CP even scalar masses are :

$$m_h^2 \simeq 2\lambda v^2, \quad m_{h'}^2 \simeq M^2, \quad m_s^2 \simeq m_S^2 - \kappa^2 v^2$$

Scalar Model

- The charged Goldstones A^0 and H^\pm 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 :

$$\Gamma(h' \rightarrow u\bar{u}) = \Gamma(A^0 \rightarrow u\bar{u}) = \Gamma(H^+ \rightarrow u\bar{d}) \simeq \frac{3y'^2 M}{16\pi},$$
$$\Gamma(h' \rightarrow sh) = \Gamma(A^0 \rightarrow sZ) = \Gamma(H^+ \rightarrow sW^+) \simeq \frac{\kappa^2 M}{16\pi}.$$

- The decay for light scalar goes via :

$$\Gamma(s \rightarrow u\bar{u}) \simeq \frac{\kappa^2 y'^2 v^2 m_s}{16\pi M^2} = \frac{g_u^2 m_s}{8\pi}.$$



References

1. Brian Batell, Ayres Freitas, Ahmed Ismail & David Mckeen, [1712.10022](#) [hep-ph]
2. Brian Batell, Ayres Freitas, Ahmed Ismail & David Mckeen, [1812.05103](#) [hep-ph]
3. P. A. Zyla et al. (Particle Data Group), PTEP 2020, 083C01 (2020).