# Renormalizable Models of Flavor-Specific Scalars

Mudit Rai (mur4@pitt.edu)

University of Pittsburgh

Collaborators : Brian Batell, Ayres Freitas, Ahmed Ismail & David Mckeen

# 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 :

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

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

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

- EFT has implications for the naturalness of the light singlet scalar, flavor violation, and CP violation.

# VLQ completion : Model

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

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

- Integrating out VLQ gives :

$$-\mathcal{L} \supset \frac{y_i\,\lambda^j}{M} S\,\overline{Q}^i_L\,u_{R\,j}\,H_c + \text{h.c.} \qquad (c_S)^j_i \equiv -y_i\,\lambda^j$$

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

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

$$\cos\theta = \frac{M}{M_{U'}}, \qquad \sin\theta = \frac{yv}{\sqrt{2}\,M_{U'}}.$$

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

# VLQ : Decays

- The decay widths for the VLQ are :

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

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

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

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

- The decay width for light scalar S :

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

# 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 :

$$\delta m_S^2 \sim \frac{\mathrm{Tr}\,\lambda^*\lambda}{16\pi^2} M^2 \quad \Rightarrow \quad \lambda^i \lesssim 4\pi \frac{m_S}{M}$$

- Correction to Higgs mass at 1 loop :

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

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

$$g_u \lesssim \frac{16\pi^2}{\sqrt{2}} \frac{m_S v}{M^2} \approx (7 \times 10^{-4}) \left(\frac{m_S}{0.1\,\mathrm{GeV}}\right) \left(\frac{2\,\mathrm{TeV}}{M}\right)^2 .$$

# 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] :

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

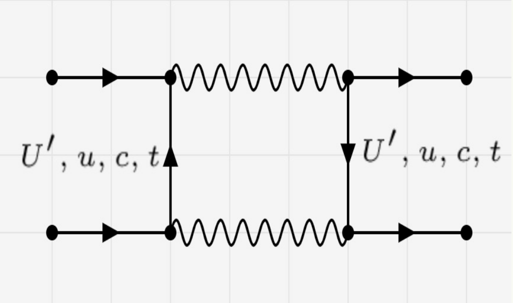
- Requiring theory prediction to be within 3 $\sigma$ gives $\sin\theta \lesssim 0.055$, implying:

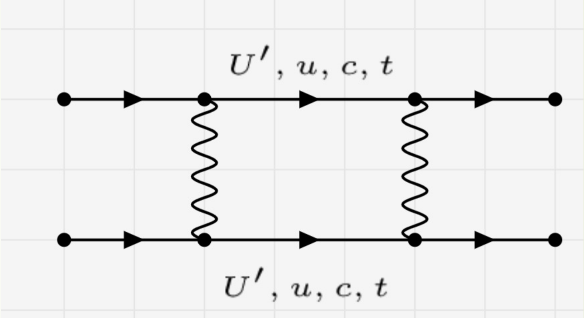
$$y \lesssim 0.6\left(\frac{M}{2\,\text{TeV}}\right).$$

# 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, $$C^{ds} = -y^4|V^*_{ud}V_{us}|^2/(128\pi^2 M^2).$$

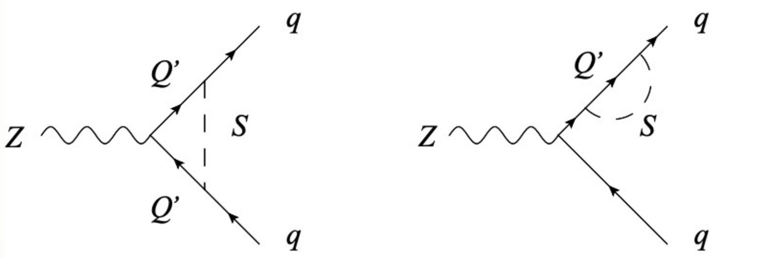
- Current limits restrict : $$\text{Re}[C^{ds}] \lesssim (10^3\,\text{TeV})^{-2}$$

- 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, $R_\ell \equiv \frac{\Gamma[Z \to \text{had.}]}{\Gamma[Z \to \ell^+ \ell^-]}$.
  1. Tree-level shift through u-U' mixing is dominant.
  2. Loops :




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

# VLQ: EDM bounds

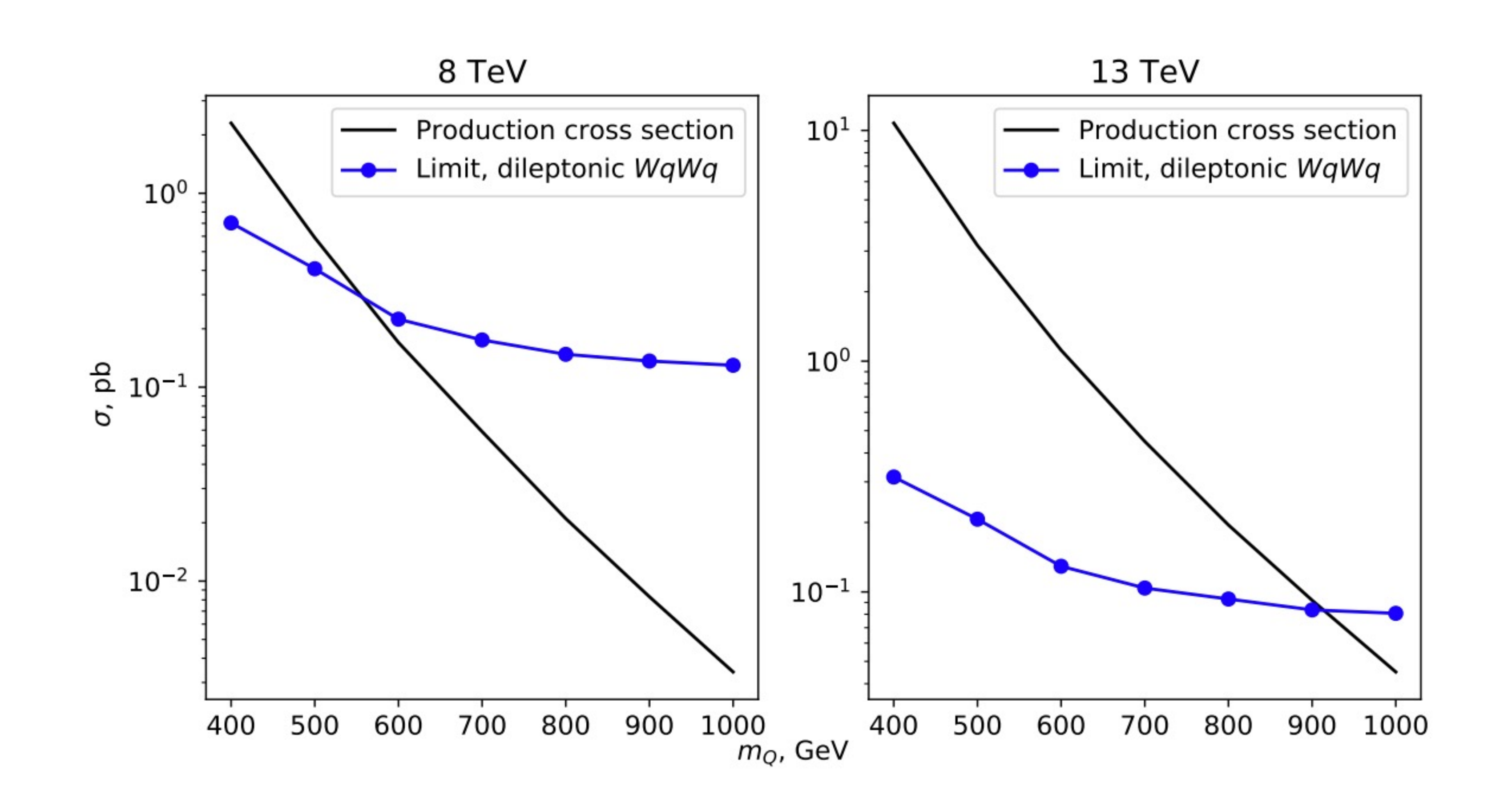
- For complex $M, y$ & $\lambda$ ,large nEDM can arise from effective CPV 4-quark operator :

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

- Neutron EDM, in this terms gives, $d_n = 0.182\, e\, C'_u \,\mathrm{GeV}$
- Experimentally, we have $|d_n| < 1.8 \times 10^{-26} e \text{ cm}$ , thus leading to :

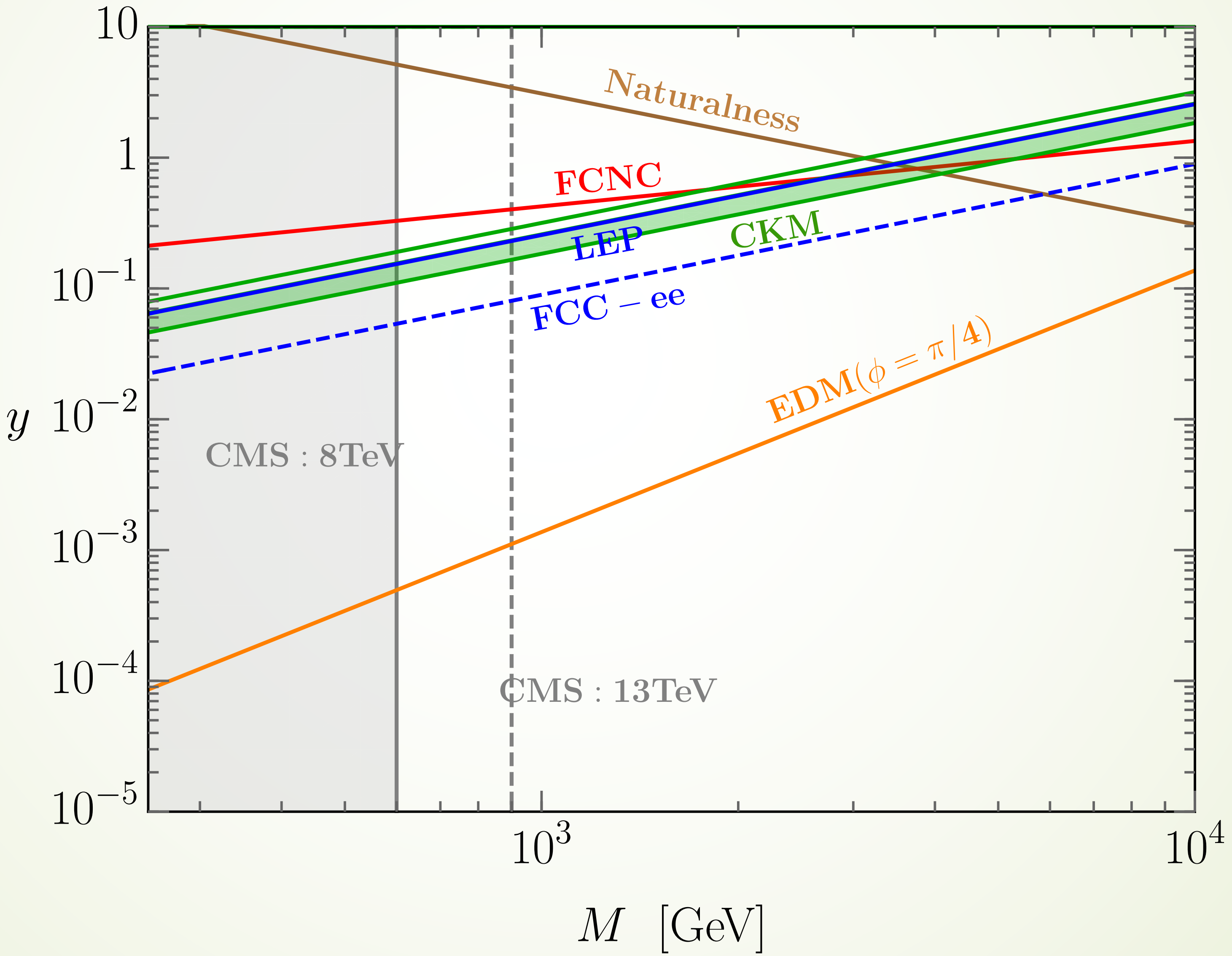
$$|g_u| \sqrt{\sin 2\phi_{\mathrm{CP}}} < 3 \times 10^{-6} \left(\frac{m_S}{1\,\mathrm{GeV}}\right)$$

# VLQ : Collider Phenomenology

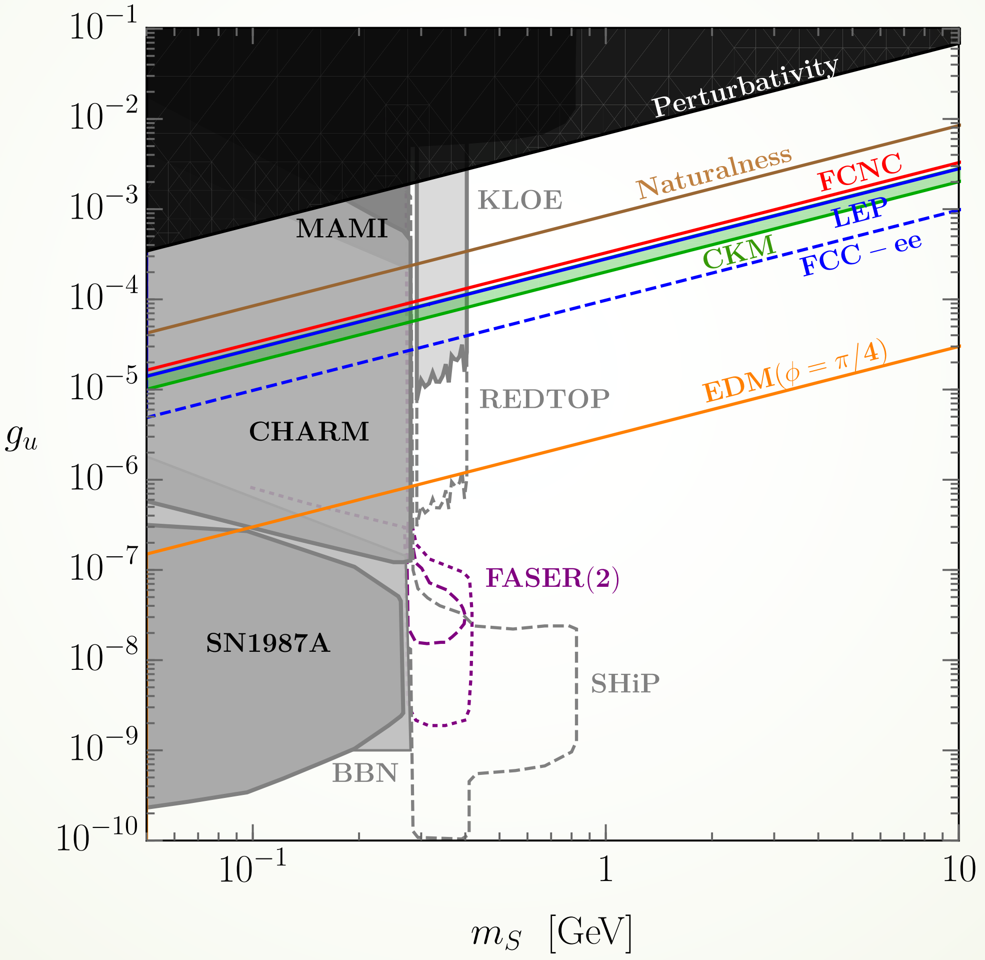



We consider pair production of U' and its decays $U' \to dW$. Assuming 20 fb$^{-1}$ at $8\ TeV$ , the constraints is $M > 550\ GeV$. At $13\ TeV$ with 300 fb$^{-1}$ luminosity, we get a constraint $M > 900\ GeV$. Analysis is close that done by CMS.

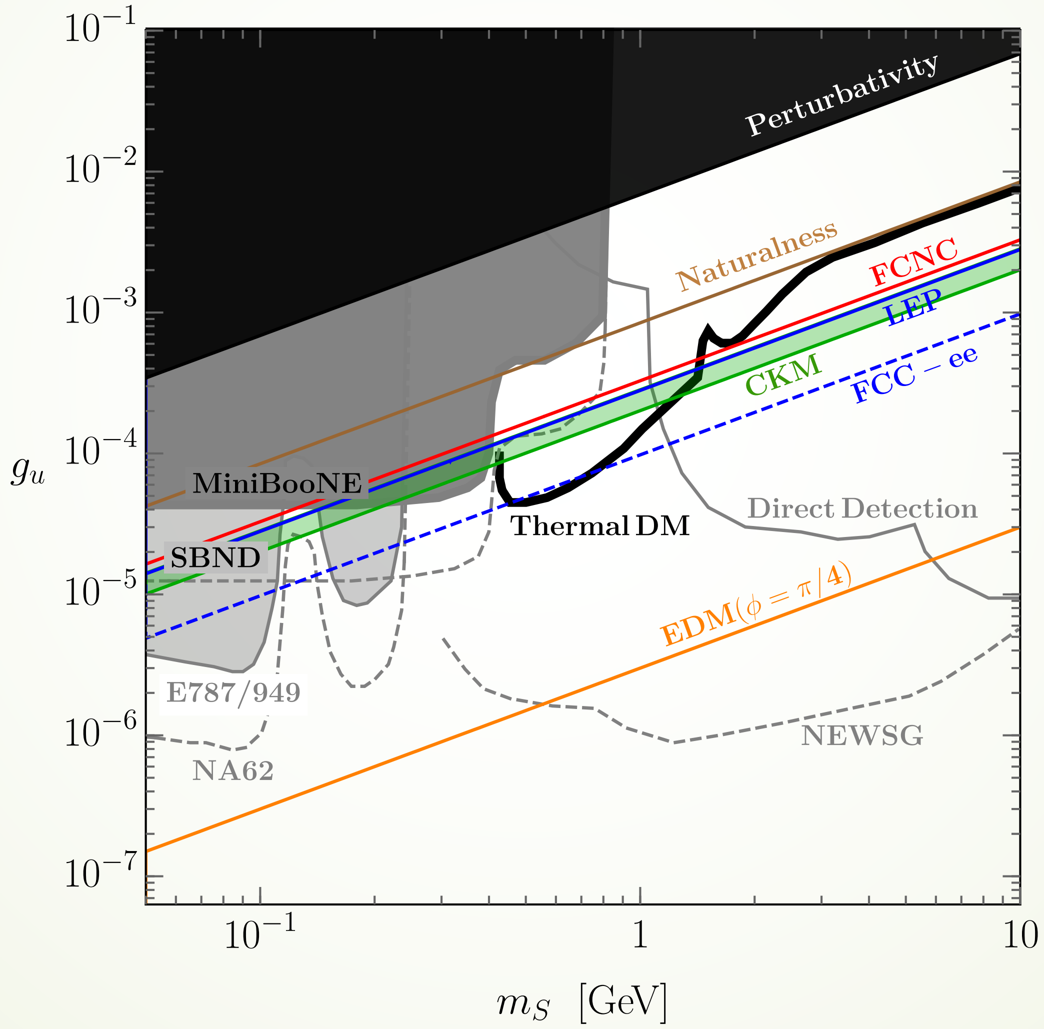
# VLQ: Results (y vs M)



# VLQ : Results (M=2 TeV) Visible Decay



# VLQ : Results (M=2 TeV) Invisible Decay



# Scalar Completion : Model

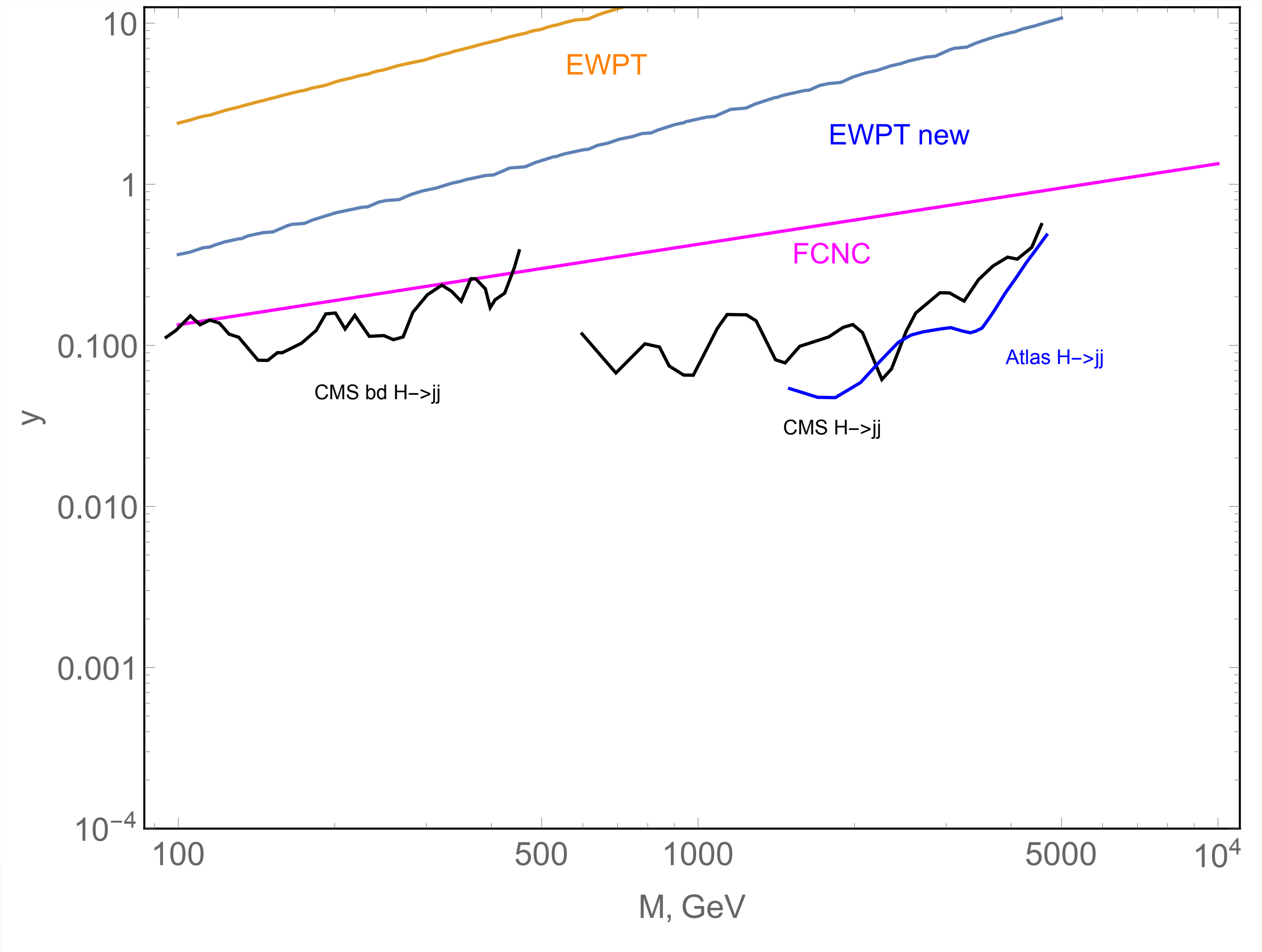
- We introduced a Higgs like scalar

$$\mathcal{L}_{\rm sd} = \mathcal{L}_{\rm SM} + \tfrac{1}{2}\partial_\mu S \partial^\mu S - \tfrac{1}{2} m_S^2 S^2 + (D_\mu H')^\dagger D^\mu H' - M^2 H'^\dagger H'$$
$$- \left[ y'^{j}_{i}\, \overline{Q^i_L}\, u_{Rj}\, H'_c + \kappa M\, S\, H^\dagger H' + \text{h.c.} \right] + \text{quartic scalar couplings},$$

- The effective dim-5 operator would be :

$$\mathcal{L} \supset \frac{\kappa\, y'^{j}_{i}}{M} S\, \overline{Q}^i_L\, u_{Rj}\, H_c + \text{h.c.}$$

# 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 :

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

- The mixing angle is $\tan\beta = \frac{v\prime}{v_0} \ll 1$
- Diagonalizing the mixed CP-even scalar fields $\varphi_i$ will lead to mass eigenstates:

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

- The CP even scalar masses are :

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

# Appendix : Scalar Model

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

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

- The leading decays of heavier scalar are :

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

- The decay for light scalar goes via :

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

# Scalar Phenomenology

- FCNC considerations :

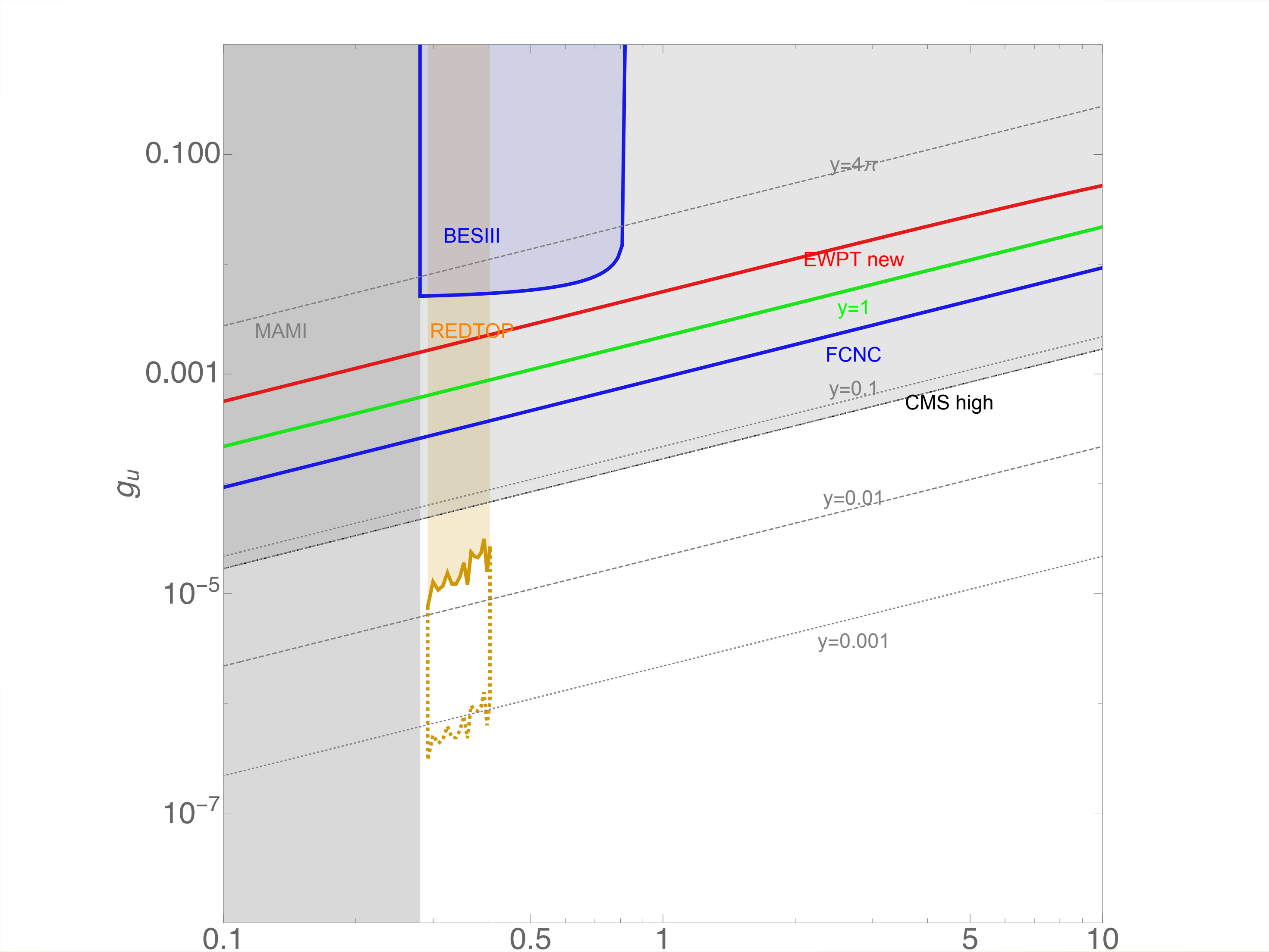
$$y \lesssim 0.6 \left(\frac{M}{2\,\mathrm{TeV}}\right)^{1/2}.$$

- Naturalness considerations :

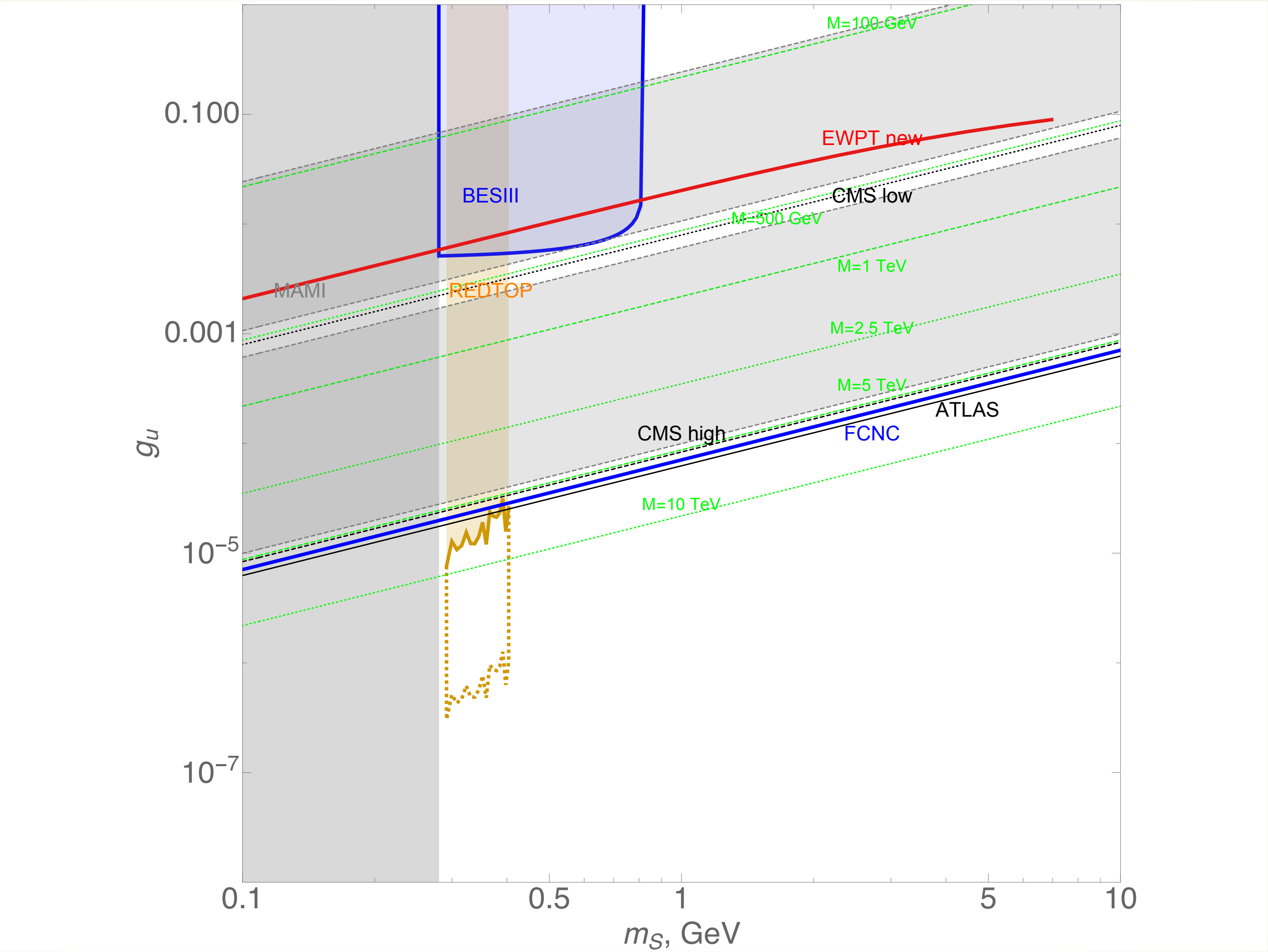
$$|\kappa| \lesssim 4\pi \frac{m_S}{M}.$$

- Electroweak precision bounds : Fixing $M = 1\,TeV, ms = 1\,GeV$,
  - $R_l^{exp} - RlSM = 0.83\ (y' = \kappa = \sqrt{4\pi})$, excluded by current data$(\delta R_l = 0.034 \pm 0.025)$
  - $R_l^{exp} - RlSM = 5.5\times10^{-3}\ (y' = \kappa = 1)$, FCC-ee : expected $\delta R_l = 0.001$.

# Scalar Completion :Results (M=2 TeV)



# Scalar Completion :Results



# 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).