Energy frontier probes of flavor specific scalar mediators

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Motivation

- New light scalar singlets feature prominently in SM extensions, e.g mediators to Dark sector.
- Apart from the Yukawa couplings, the new scalar-fermionic couplings tend to break the flavor symmetry, leading to possibility of new large FCNC's.
- A standard way to evade is via the MFV hypothesis, with new couplings $\propto Y_u, Y_d$.
- The flavor-specific hypothesis takes a different route by having couplings to only one flavor in the mass basis.

Motivation

- This is a technically natural, radiatively stable hypothesis
- We will explore two UV complete 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 complementary to those in the EFT[1,2].
- In these models, the low energy and high energy frontiers can be linked via the interpolation of experimental constraints both ways.

EFT Review

- Light scalar S with flavor-specific couplings :

$$\mathcal{L} \supset i\bar{\chi}(\not{D} - m_\chi)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \left(g_\chi S \bar{\chi}_L \chi_R + \frac{c_S}{M} S \bar{Q}_L U_R H_c + \text{h.c.}\right)$$

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

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

- EFT has implications for the naturalness of the light singlet scalar, flavor violation, and CP violation[1,2].

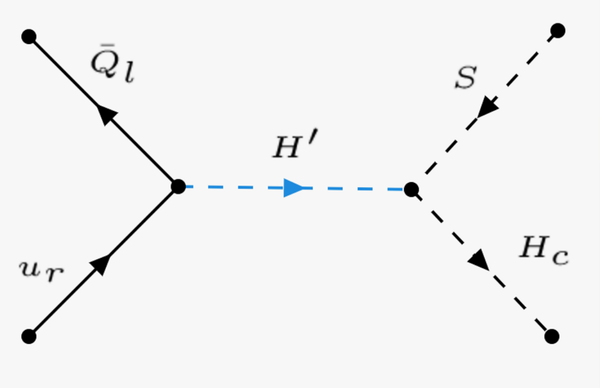
Scalar Completion: Model

- 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 :

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



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 $\tan\beta = \frac{v'}{v_0} \ll 1$
- Diagonalizing the mixed CP-even scalar fields φ_i will lead to mass eigenstates:

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

- The CP even scalar masses are :

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

Decays

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

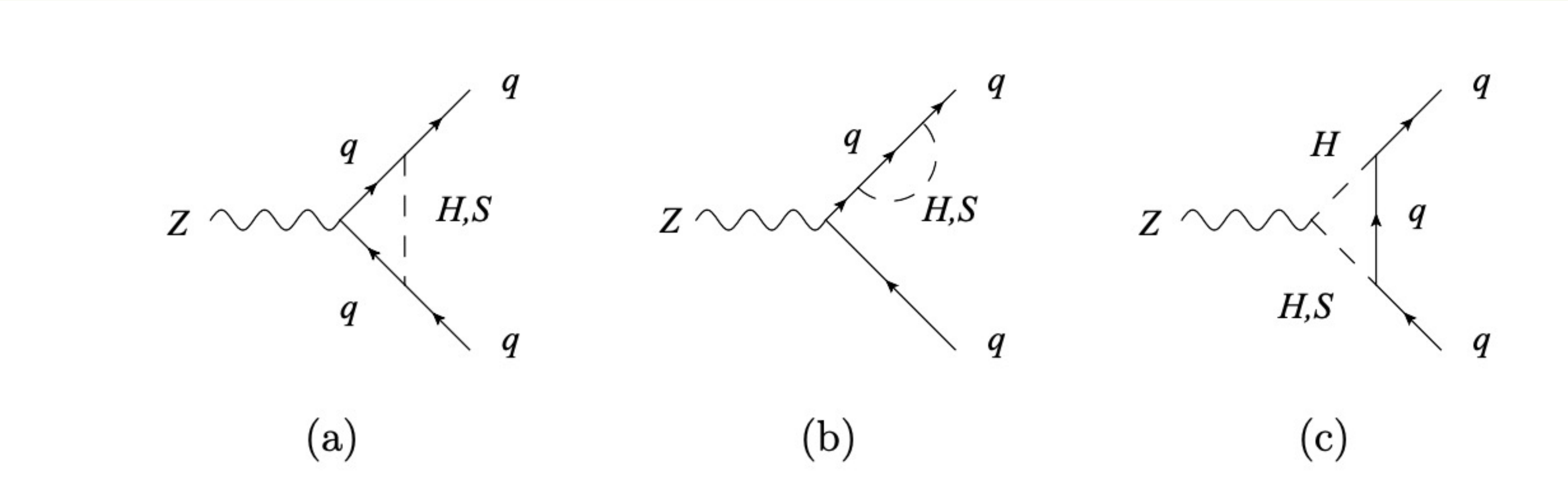
$$m^2_{A^0,H^\pm} = M^2\cos^2\beta + (\mu'^2 - \kappa M v_s)\sin(2\beta) - \mu^2\sin^4\beta \approx M^2$$

- 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 into an invisible DM will happen for $m_s > 2m_\chi$.

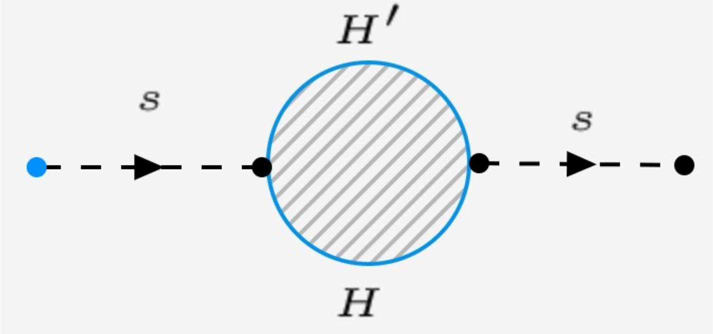
Scalar Phenomenology : EWPT



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

Scalar Phenomenology

- Naturalness considerations :



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

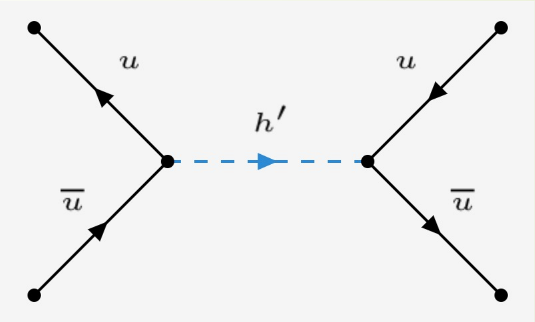
Another limit arises if we integrate out H' and put Higgs to its vev:

$$|\kappa| \lesssim \frac{m_S}{v}$$

- Collider Phenomenology:

  Can be observed at LHC as

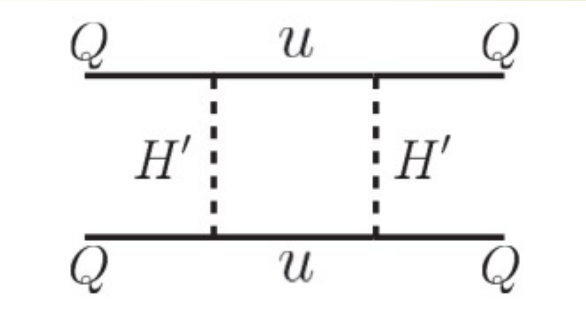
  Dijet resonances.



Scalar Phenomenology

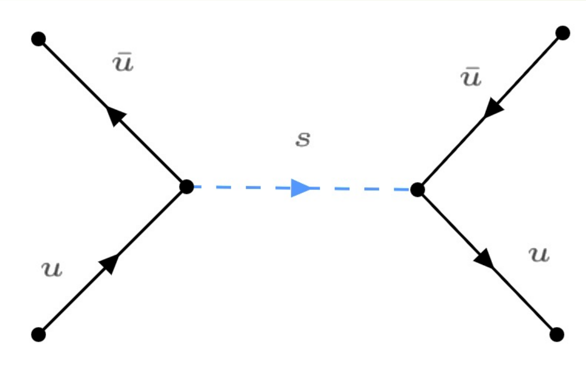
- FCNC considerations (K^0 system) :

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

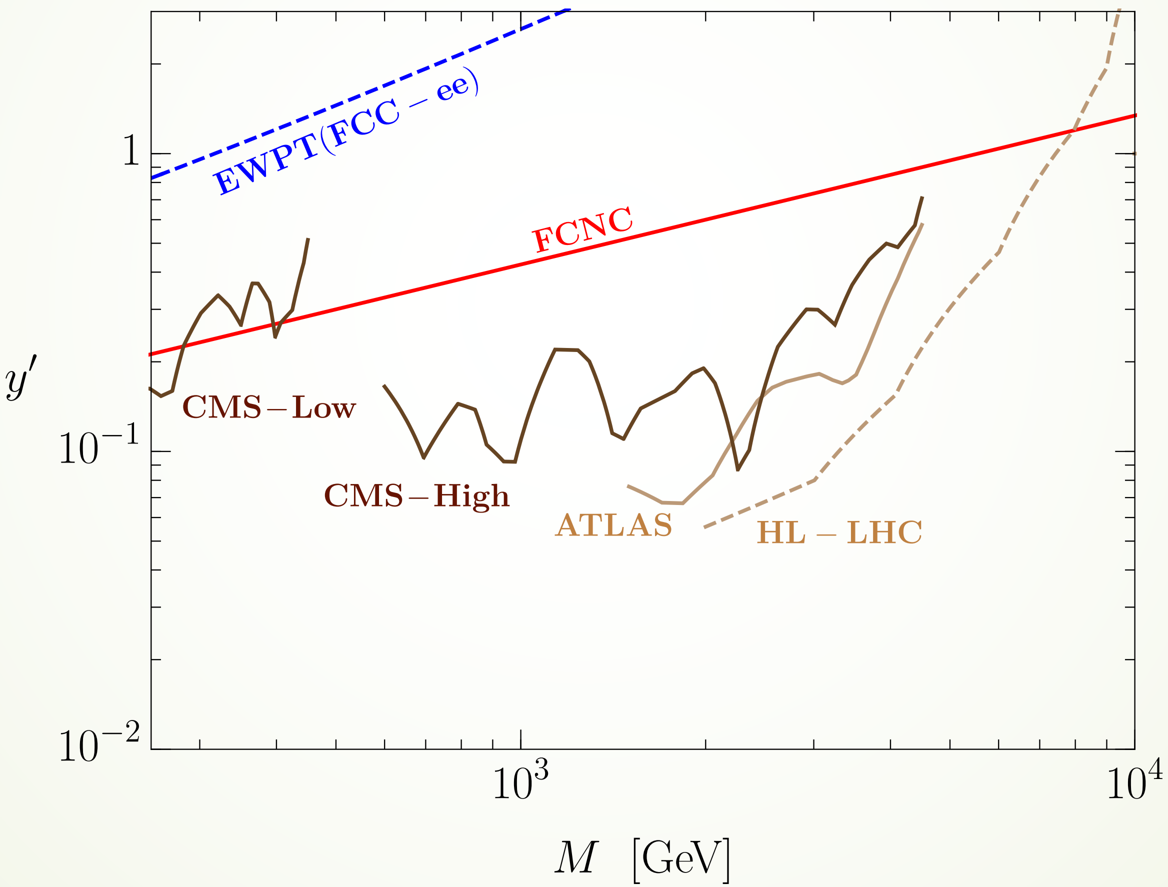


- Neutron EDM from 4-up operator:

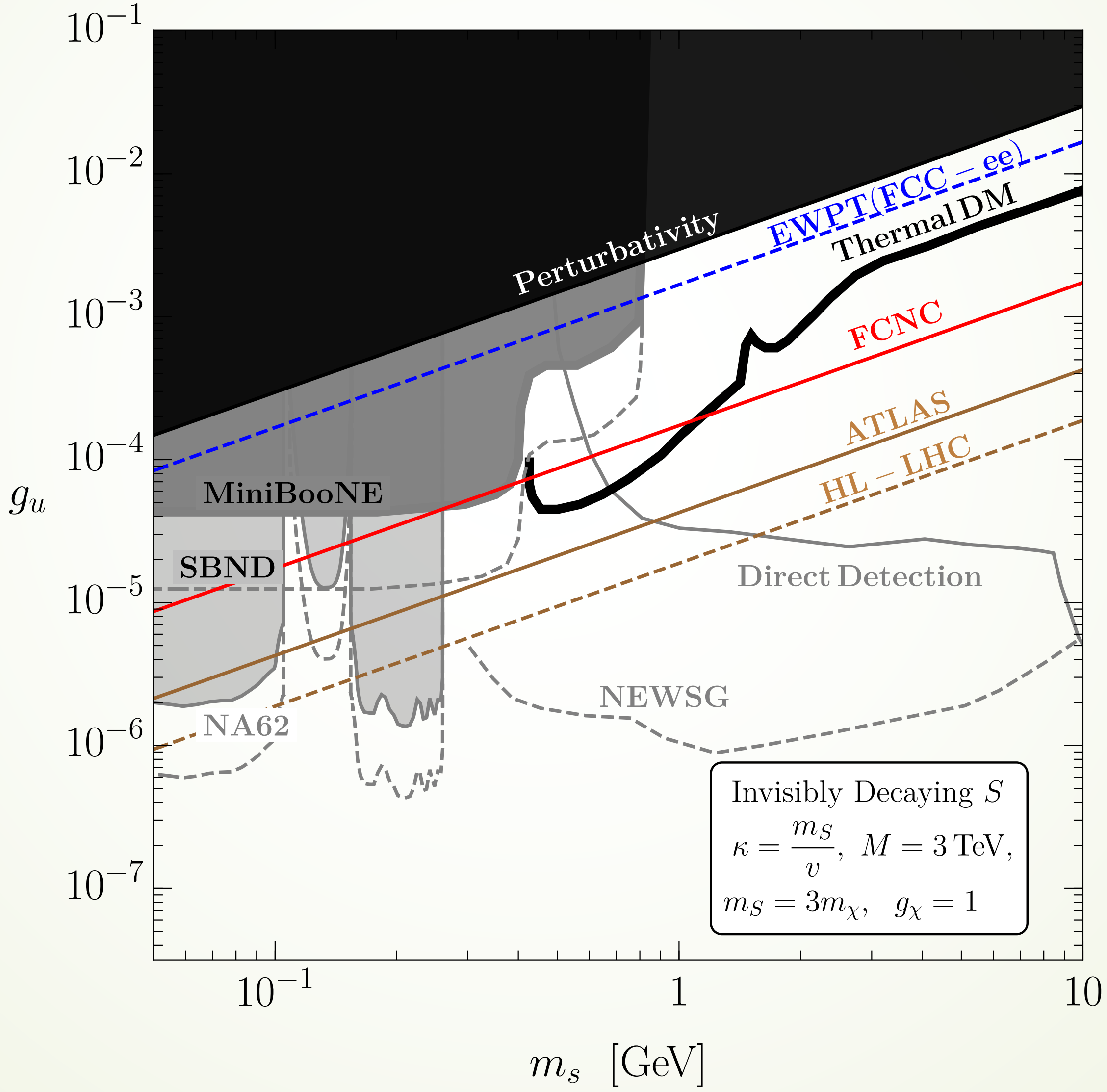
$$|g_u|\sqrt{\sin 2\phi_{\text{CP}}} < 3 \times 10^{-6} \left(\frac{m_S}{1\,\text{GeV}}\right)$$



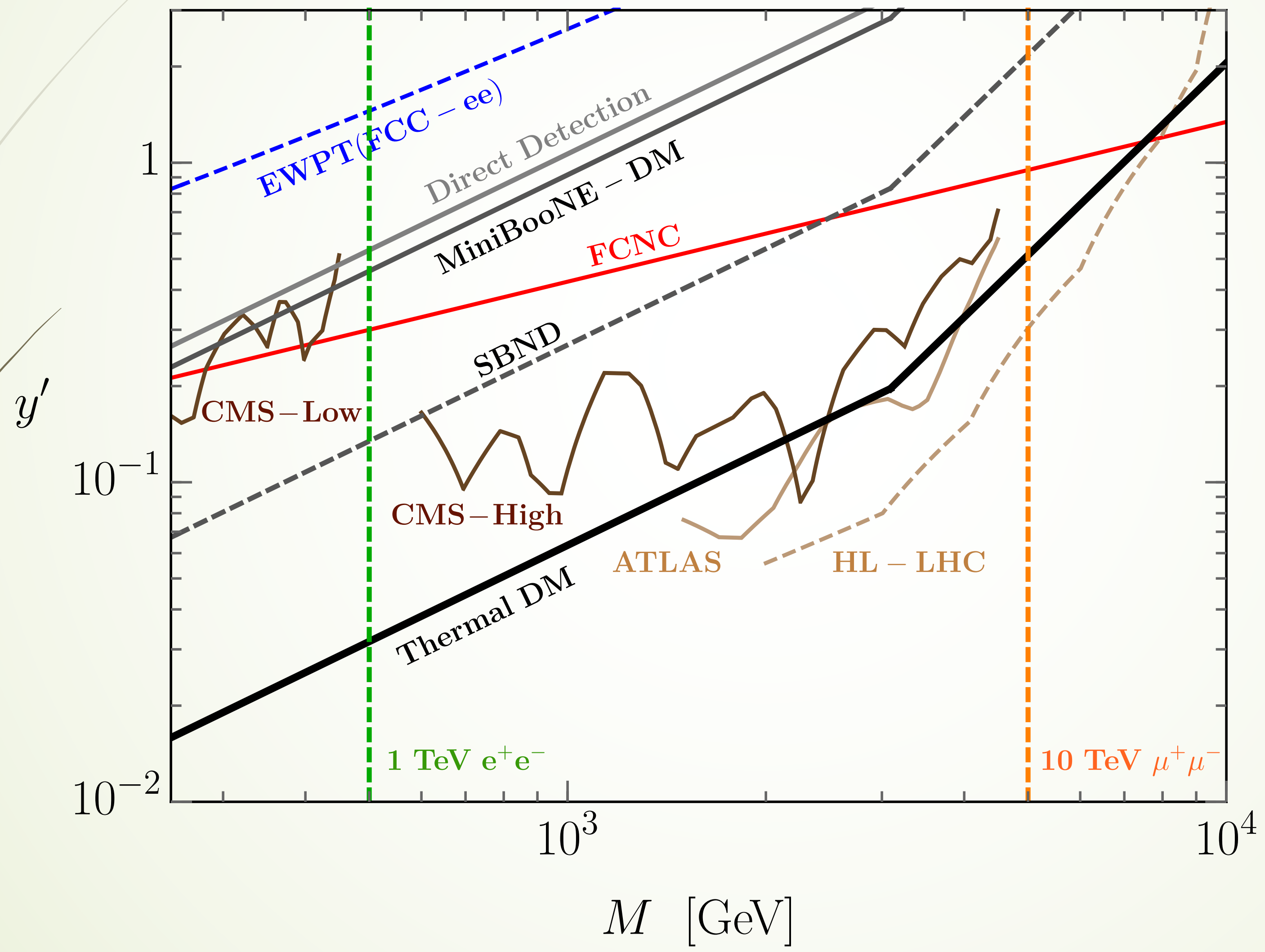
High Energy Plots



Low Energy DM Plot



Bridging the energy scales



$m_S = 0.5\,GeV;\; g_\chi = 2$

$$\kappa = \min\left\{\frac{4\pi m_s}{M}, \frac{m_s}{v}\right\}$$

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 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 complimentary constraints on the parameter space.

Thank you!

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.

Appendix : 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 :

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

Appendix : 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 :

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

Appendix : 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] :

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

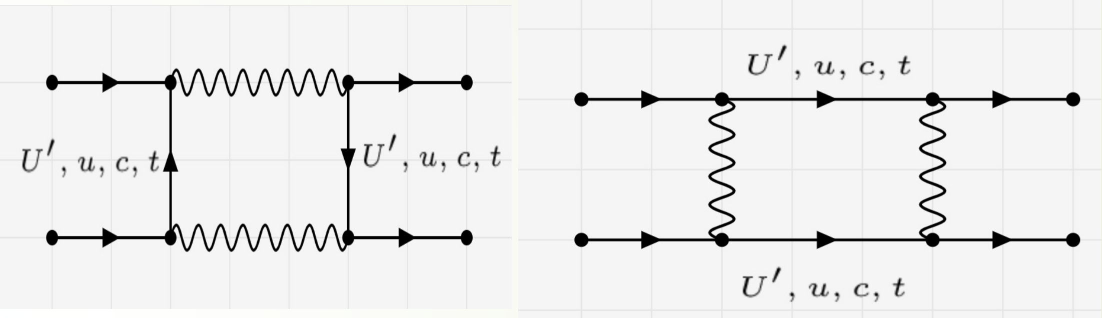
- Requiring theory prediction to be within 3 σ gives $\sin\theta \lesssim 0.055$, implying:

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

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

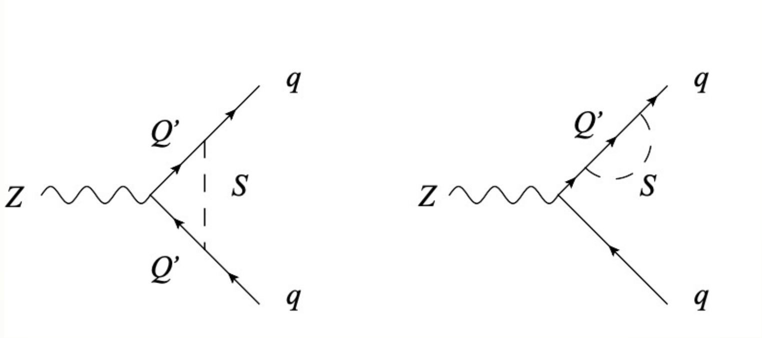
- Current limits restrict : $$\text{Re}[C^{ds}] \lesssim (10^3\,\text{TeV})^{-2}$$

- This can be translated as :

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

Appendix : 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(LEP) 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 $\frac{yv}{M} < 0.022$.

Appendix : VLQ: EDM bounds

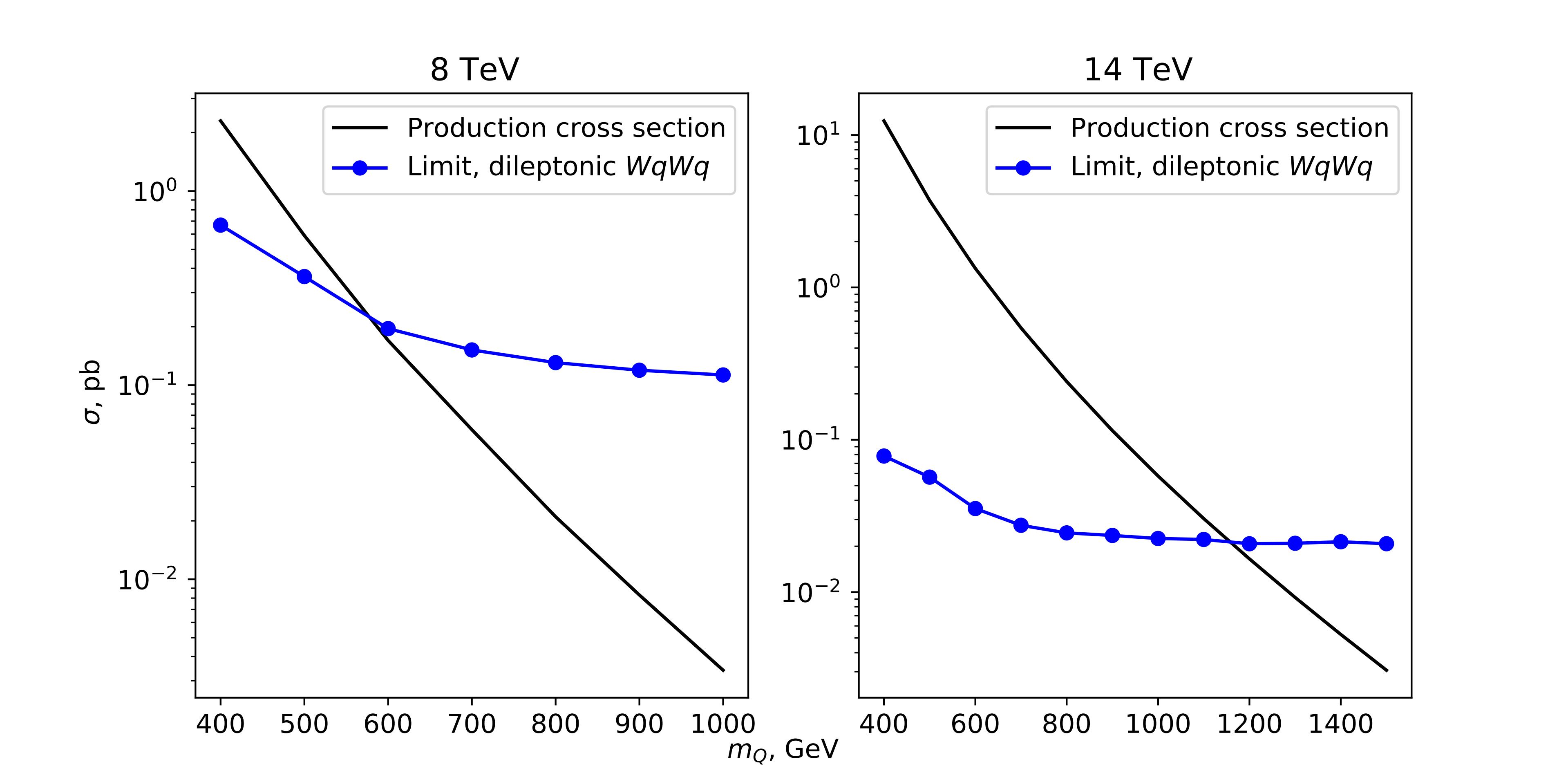
- For complex M, y & λ ,large nEDM can arise from effective CPV 4-quark operator :

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

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

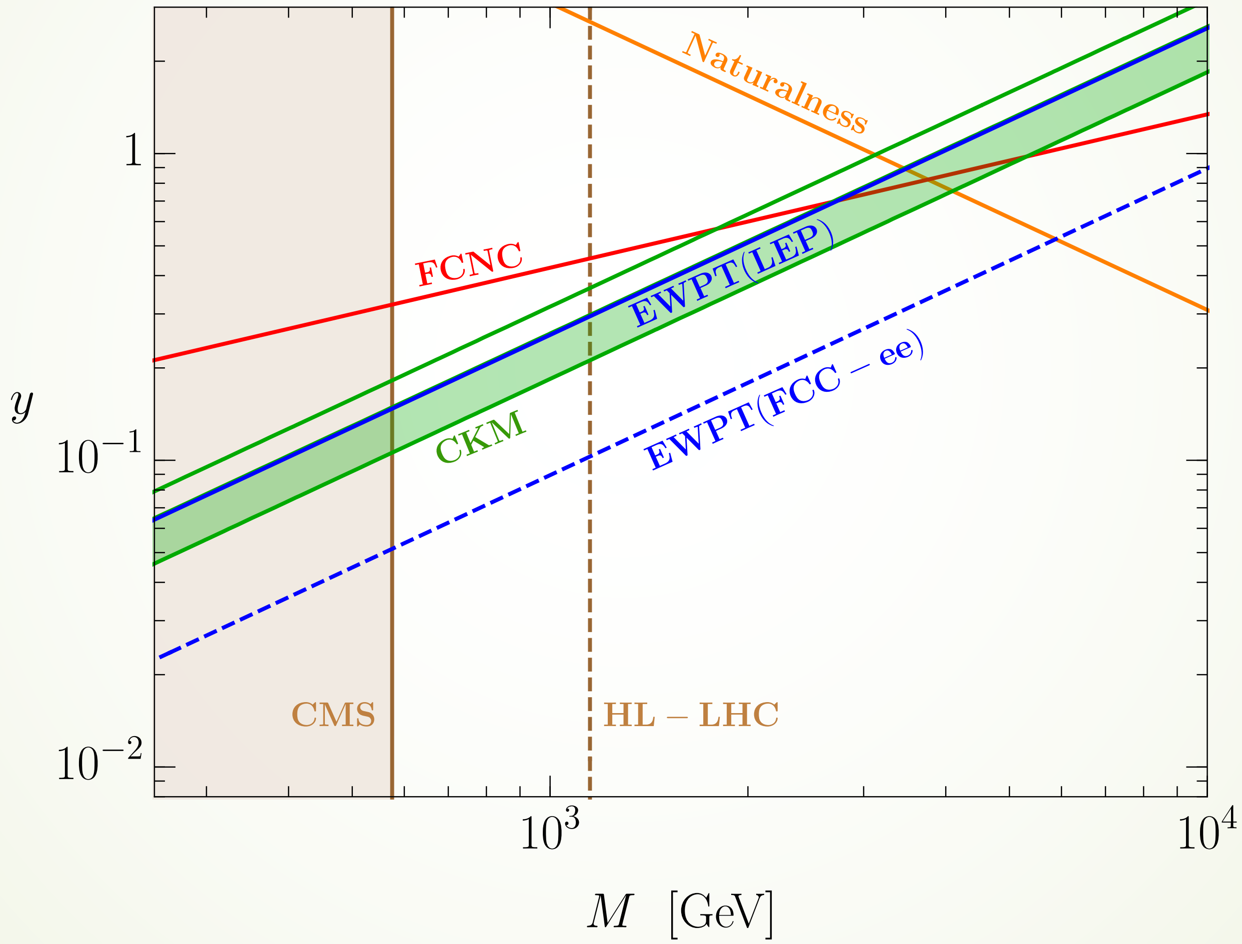
$$|g_u|\sqrt{\sin 2\phi_{\mathrm{CP}}} < 3 \times 10^{-6} \left(\frac{m_S}{1\,\mathrm{GeV}}\right)$$

VLQ : Collider Phenomenology

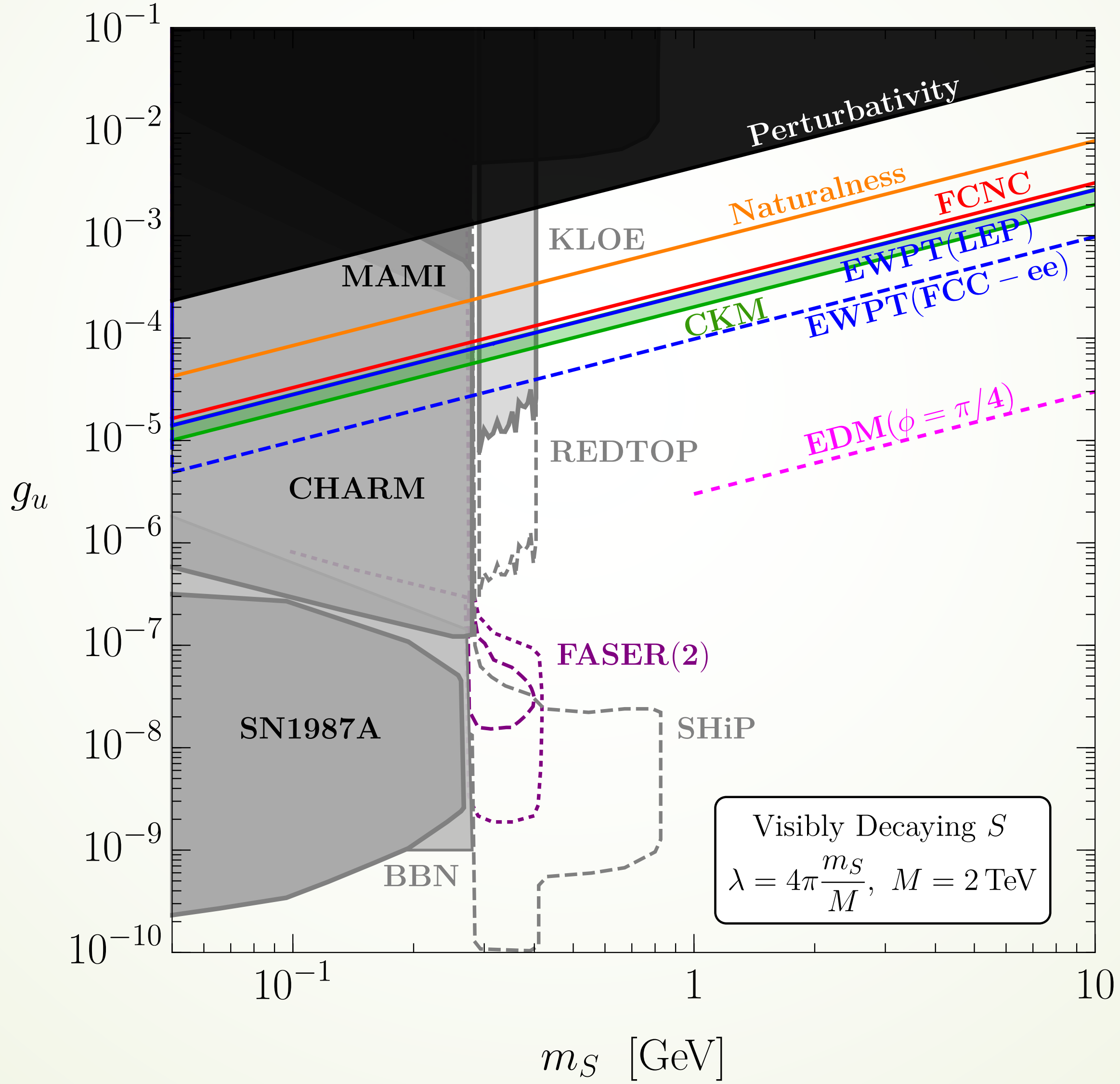


We consider pair production of U' and its decays $U' \to dW$. Assuming 20 fb^{-1} at 8 TeV , the constraints is $M > 575\ GeV$. At 14 TeV with 3000 fb^{-1} luminosity, we get a constraint $M > 1150\ GeV$. Analysis is close to that done by CMS.

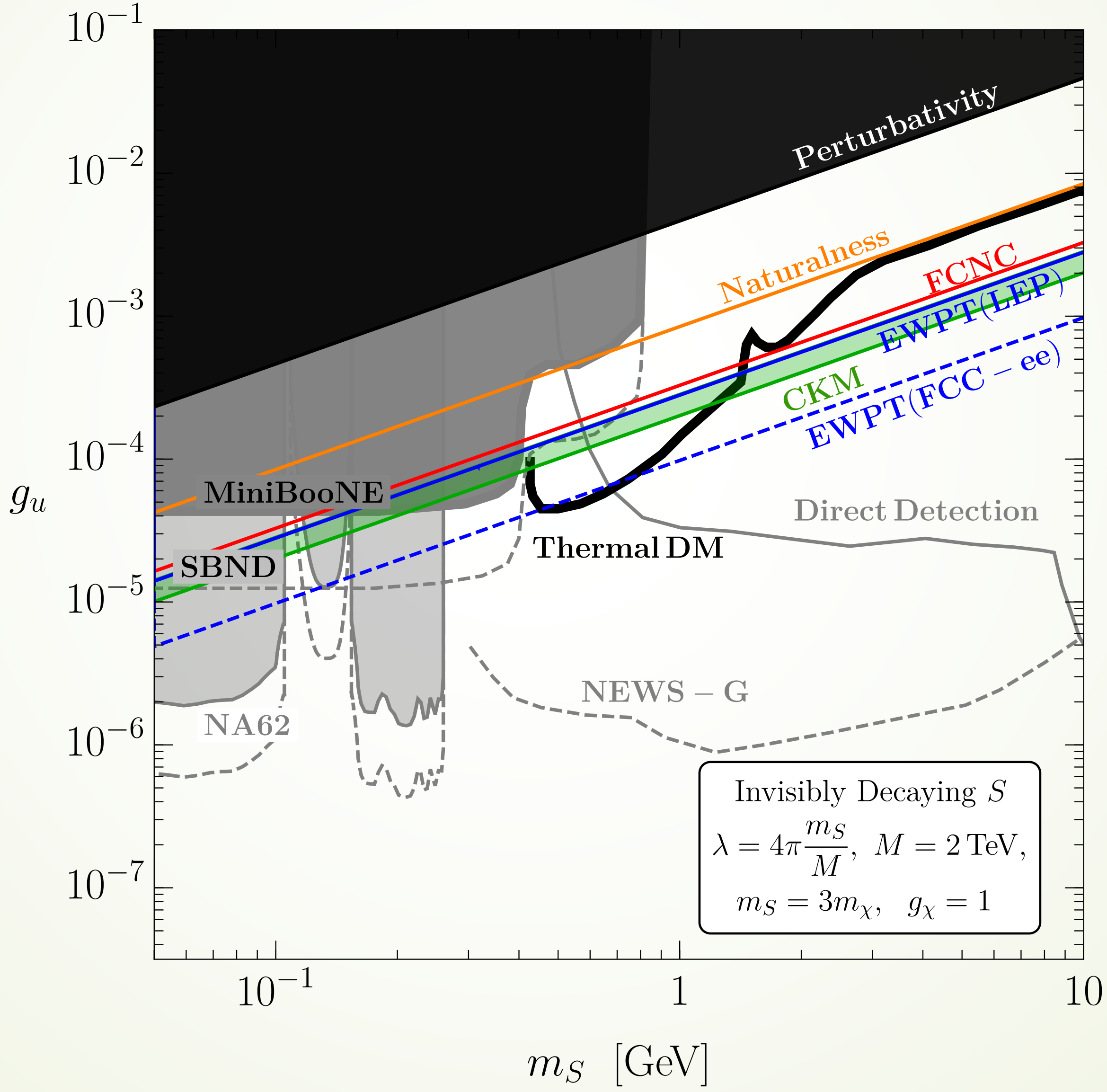
VLQ: Results (y vs M)



VLQ : Results (Visible Decay)



VLQ : Results (Invisible Decay)



EFT Structure Basics

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

- In Flavor hypothesis, we have

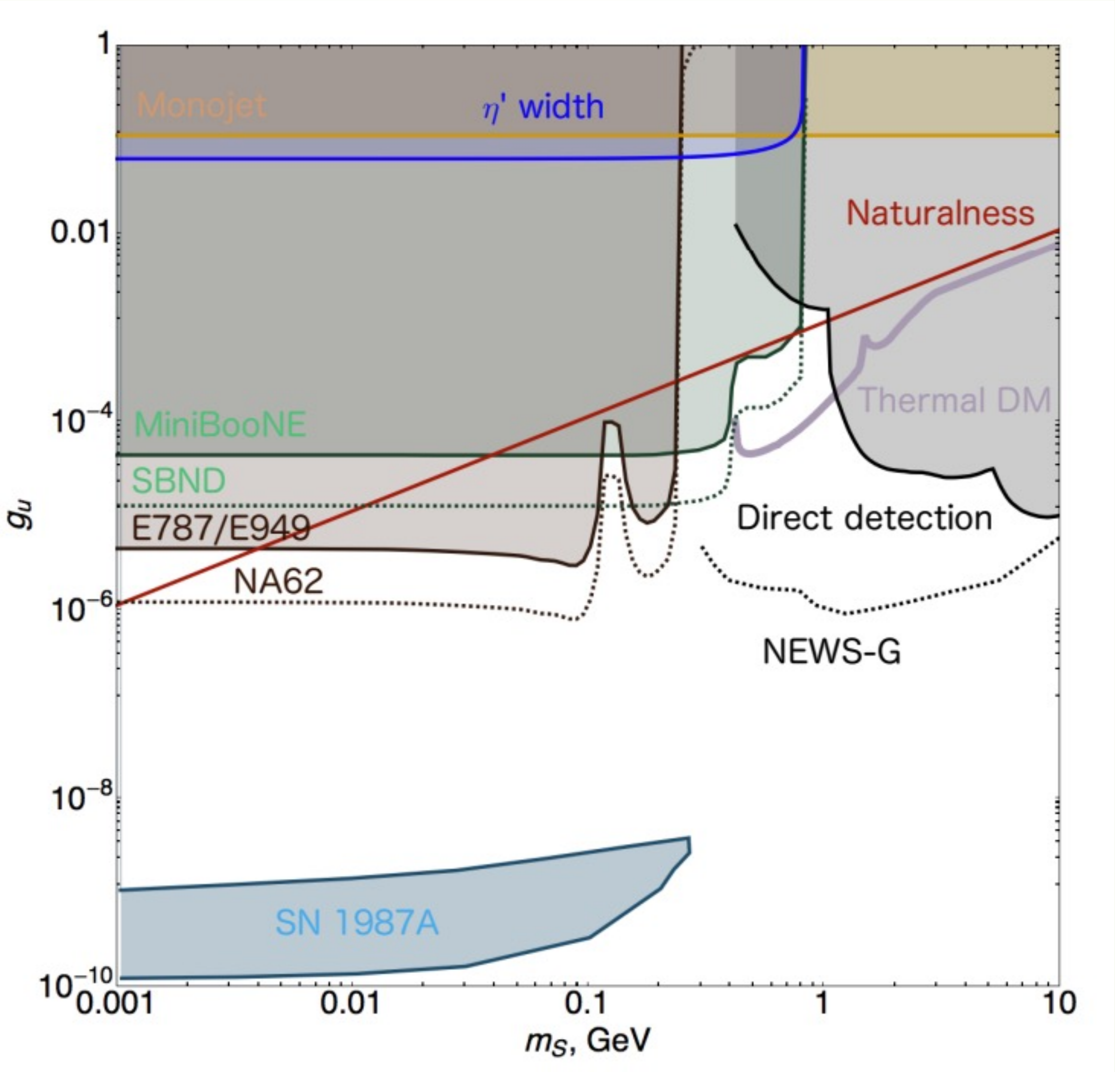
$$c_S \propto \text{diag}(1,0,0)$$

- This breaks the flavor symmetry as

$$U(3)_Q \times U(3)_U \to U(1)_u \times U(2)_{ctL} \times U(2)_{ctR}.$$

- In our flavor-specific scenario, in addition to the Yukawa couplings, we are adding a new flavor-breaking spurion c_s, and assume that it is aligned with the Yukawa coupling Y_u.

EFT Dark Sector Plot [2]



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).