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Light Higgs and Vector-like Quarks without Prejudice

Based on JHEP 1307 (2013) 155 and references therein

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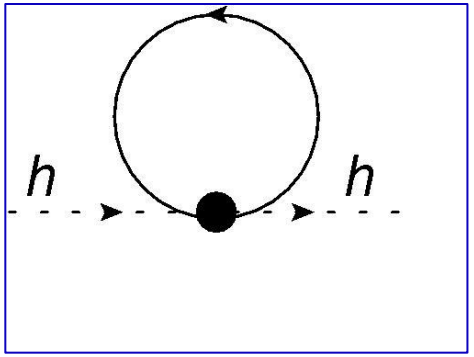
Why Vector-like Quarks?

- Vector-like Quarks (VLQ)?
  - Color triplet spin 1/2 fermions
  - Left and right spinors in the same representation
- Why VLQ?
  - No gauge anomalies
  - Models addressing the EW hierarchy problem
  - Expected to be light: $(m_f \lesssim 1\ \mathrm{TeV})$



After canceling Λ^2 term

$$\delta m_h^2 \approx \frac{3m_t^2}{4\pi^2 v^2} m_f^2 \log \frac{\Lambda^2}{m_f^2}$$

Scope

- SM + single VLQ representation
- Consider VLQ representations of the SM chiral quarks:
  - Singlet up-like VLQ: (**3**,1,2/3)
  - Singlet down-like VLQ: (**3**,1,-1/3)
  - Doublet VLQ: (**3**,2,1/6)
- Phenomenology (Flavor, EWPO)
  - Renormalizable level
  - Leading higher dimensional terms: $H^\dagger H \bar{q}_i Q,\ H^\dagger H \overline{Q} Q$
- **Implications for the Higgs boson**

Renormalizable VLQ models

- Mass term in the weak (chiral) basis

$$-\mathcal{L}_{\rm mass} = \bar{u}^i_L \mathcal{M}^{ij}_u u^j_R + \bar{d}^i_L \mathcal{M}^{ij}_d d^j_R + \text{h.c.}$$

- Bi-unitary rotations

$$\mathcal{M}_{u,d,\rm diag} = U^{u,d}_L \mathcal{M}_{u,d} U^{u,d\dagger}_R$$

- Interactions in the physical (mass) eigenbasis

$$V^L_{ij} \equiv (U^d_L)^*_{jk}(U^u_L)_{ik} \qquad V^R_{ij} \equiv (U^d_R)^*_{jk}(U^u_R)_{ik}$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}(V^L_{ij}\bar{u}^i\gamma^\mu P_L d^j + V^R_{ij}\bar{u}^i\gamma^\mu P_R d^j)W^+_\mu + \text{h.c.}\,,$$

$$\mathcal{L}_Z = -\frac{g}{2c_W}\left(X^u_{ij}\bar{u}^i\gamma^\mu P_L u^j - X^d_{ij}\bar{d}^i\gamma^\mu P_L d^j + Y^u_{ij}\bar{u}^i\gamma^\mu P_R u^j - Y^d_{ij}\bar{d}^i\gamma^\mu P_R d^j - 2s^2_W J^\mu_{\rm EM}\right)Z_\mu\,,$$

$$\mathcal{L}^{(0)}_h = -(X^u_{ij} - Y^u_{ij})\frac{m_j}{v}\bar{u}^i P_R u^j h - (X^d_{ij} - Y^d_{ij})\frac{m_j}{v}\bar{d}^i P_R d^j h + \text{h.c.}\,,$$

$$X^u \equiv V^L V^{L\dagger} \qquad Y^u \equiv V^R V^{R\dagger} \qquad X^d \equiv V^{L\dagger} V^L \qquad Y^d \equiv V^{R\dagger} V^R$$

✓ **Higgs interactions fixed by the neutral current interactions**

Singlet up-like VLQ

- Renormalizable Lagrangian

$$-\mathcal{L}_U^{(0)} = y_d^{ij}\,\bar{q}_L^i H d_R^j + y_u^{ij}\,\bar{q}_L^i \tilde{H} u_R^j + y_U^i \bar{q}_L^i \tilde{H} U_R + M_U \bar{U}_L U_R + \text{h.c.}$$

- Mass matrices (V^R=0, $Y^{u,d}$=0, X^d=1)

$$\mathcal{M}_u = \begin{pmatrix} y_u v/\sqrt{2} & y_U v/\sqrt{2} \\ 0 & M_U \end{pmatrix}, \quad \mathcal{M}_d = (y_d v/\sqrt{2})$$

- Tree level constraints

$$|X^u - \mathbb{I}|_{3\times 3} < \begin{bmatrix} 0.001 & 2.1\times 10^{-4} & 0.14 \\ & 0.0026 & 0.14 \\ & & 0.13 \end{bmatrix}$$

D-$\overline{\text{D}}$ mixing

t → Z q

CKM non-unitarity,
Z → qq

Singlet up-like VLQ: t – T system

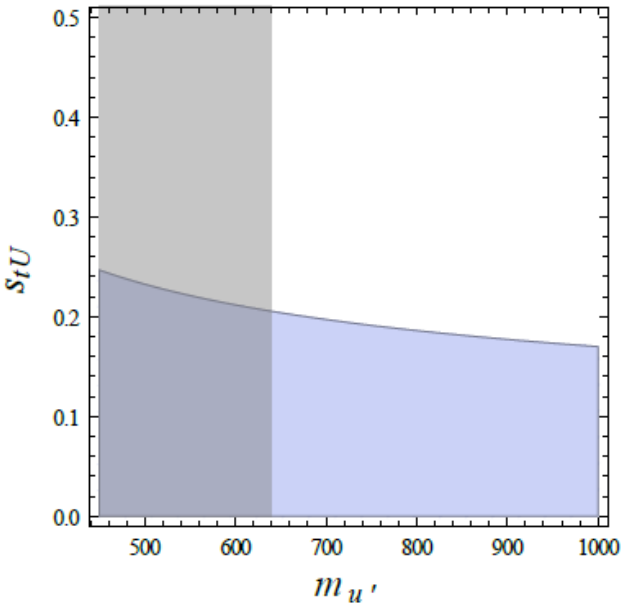
- Neglecting the mixing with the first two generations

$$\tan(2\theta_{tU}) = \frac{\sqrt{2} v y_U^t M_U}{M_U^2 - [(y_u^t)^2 + (y_U^t)^2] v^2/2}\,,$$

$$m_t m_{u'} = M_U y_u^t \frac{v}{\sqrt{2}}\,, \qquad m_t^2 + m_{u'}^2 = M_U^2 + \frac{v^2}{2}[(y_u^t)^2 + (y_U^t)^2]\,.$$

- t – T mixing constrained from the ρ parameter

$$\Delta\rho = \frac{\alpha N_C}{16\pi s_W^2}\frac{m_t^2}{m_W^2} s_{tU}^2 \left[-(1+c_{tU}^2) + s_{tU}^2 r + 2c_{tU}^2 \frac{r}{r-1}\log(r)\right]$$



- Higgs (and Z) couplings:

$$X_{tt}^u = c_{tU}^2,\; X_{tu'}^u = c_{tU} s_{tU} \text{ and } X_{u'u'}^u = s_{tU}^2$$

✓Negligible deviations in the Higgs production and decays

Singlet down-like VLQ

- Renormalizable Lagrangian

$$-\mathcal{L}_D^{(0)} = y_d^{ij}\bar{q}_L^i H d_R^j + y_u^{ij}\bar{q}_L^i \tilde{H} u_R^j + y_D^i \bar{q}_L^i H D_R + M_D \bar{D}_L D_R + \text{h.c.}$$

- $V^R=0$, $Y^{u,d}=0$, $X^u=1$

- Tree level constraints

$$|X^d - \mathbb{I}|_{3\times 3} < \begin{bmatrix} 0.004 & 1.4\times 10^{-5} & 4\times 10^{-4} \\ & 0.006 & 0.001 \\ & & 0.0057 \end{bmatrix}$$

$K_L \to \mu\mu$, $B_{d,s} \to \mu\mu$

APV, $Z \to qq$

✓ Higgs properties remain SM-like!

Doublet VLQ

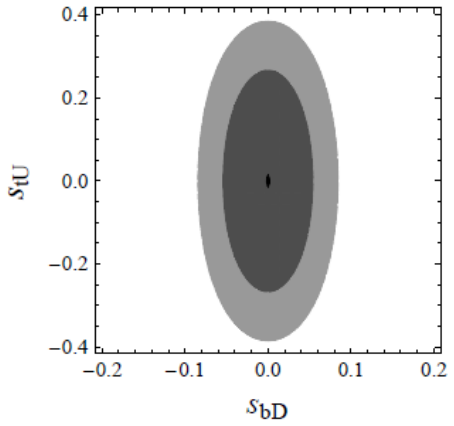
- Mass terms (V^L unitary, $X^{u,d}$=1)

$$\mathcal{M}_u = \begin{pmatrix} y_u v/\sqrt{2} & 0 \\ y_U v/\sqrt{2} & M_Q \end{pmatrix}, \quad \mathcal{M}_d = \begin{pmatrix} y_d v/\sqrt{2} & 0 \\ y_D v/\sqrt{2} & M_Q \end{pmatrix}$$

- Tree level constraints

$$|Y^u|_{3\times 3} < \begin{bmatrix} 0.11 & 2.1\times 10^{-4} & 0.14 \\ & 0.018 & 0.14 \\ & & - \end{bmatrix}, \quad |Y^d|_{3\times 3} < \begin{bmatrix} 0.1 & 1.4\times 10^{-5} & 4\times 10^{-4} \\ & 0.21 & 0.001 \\ & & 0.03 \end{bmatrix}$$

- t-T and b-B system
  - Mass splitting and mixing angles related
  - Mixing angles constrained from Z->bb
  - Mass splitting from ρ parameter



✓Higgs properties remain SM-like!

Non-renormalizable VLQ models

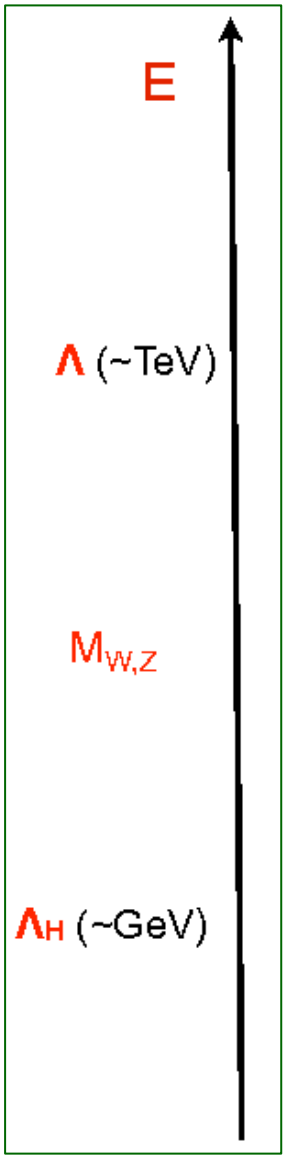
- Including dimension five operators

$$H^\dagger H \bar{q}_i Q,\ H^\dagger H \bar{Q} Q$$

- Example: Singlet up-like VLQ
- Preserve mass diagonalization procedure of the renormalizable models

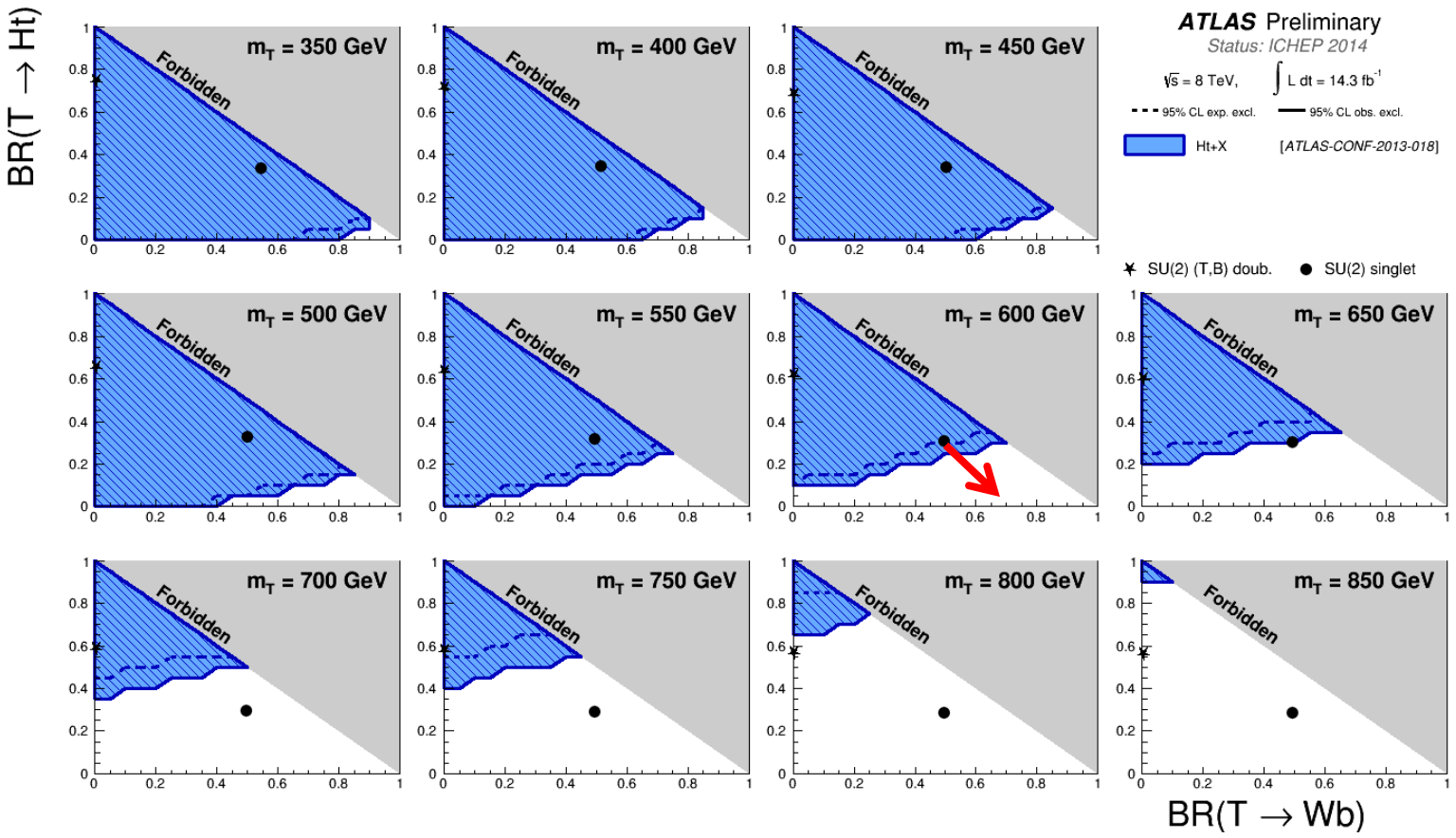
$$M_U \to M_U + c_2 \frac{v^2/2 - |H|^2}{\Lambda}\ ,\ -\mathcal{L}_U^{(1)} = c_1^i \frac{v^2/2 - |H|^2}{\Lambda} \bar{U}_L u_R^i$$

- Flavor structure of gauge interactions unchanged
- New contribution to Higgs interactions!



Implications for VLQ direct searches

- Renormalizable models: fixed branching ratios for T → th, Wb, Zt
- **New contribution to T → ht**



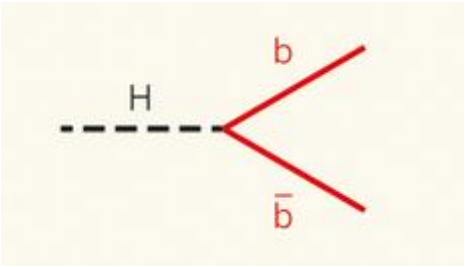
Implications for Higgs physics

- Including dimension five operators (mass basis)

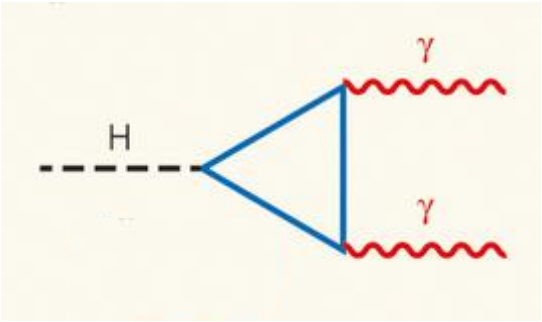
$$\mathcal{L}_h^{(1)} = \left(\frac{X_{ij}^{u\prime}}{\Lambda} \bar{u}_L^i u_R^j + \frac{X_{ij}^{d\prime}}{\Lambda} \bar{d}_L^i d_R^j \right) \left[vh + \frac{h^2}{2} \right] + \text{h.c.}$$

  - Single Higgs couplings - **not related to weak currents!**
  - Di-Higgs couplings

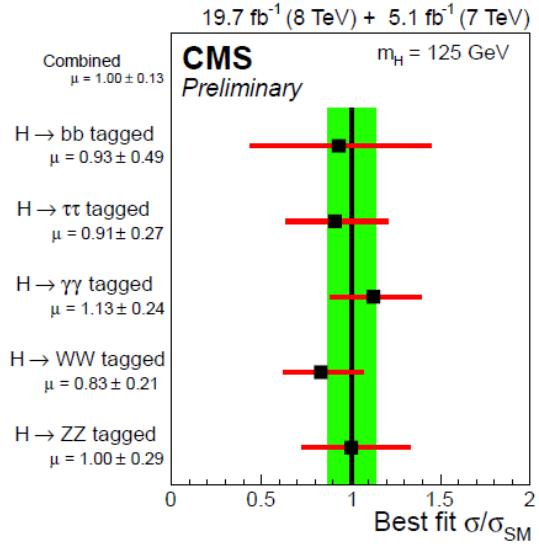
- Flavor violating Higgs couplings
  - K, D, B meson mixings – severe constraints
  - ✓ **t → hq**

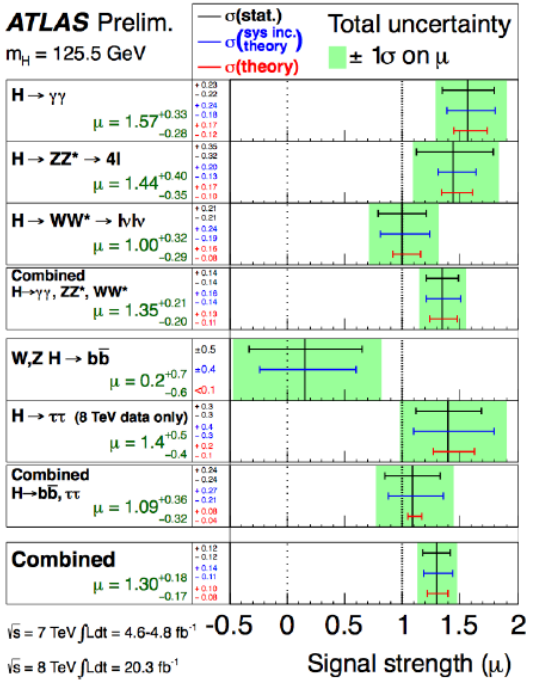


- Flavor diagonal Higgs couplings
  - ✓ **h → bb, cc, ss, dd, uu**
- Loop induced Higgs processes
  - ✓ **h → γγ, gg → h**

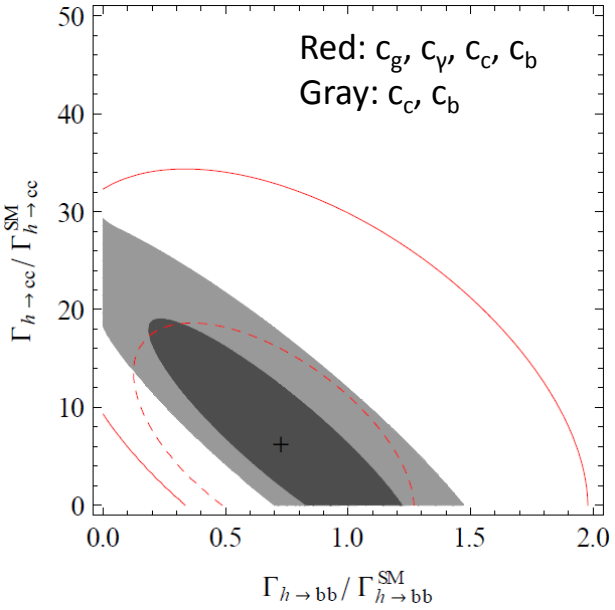


Impact of the existing LHC Higgs data



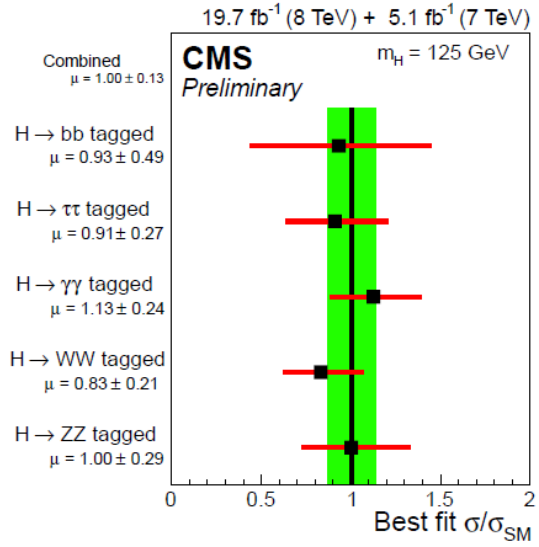


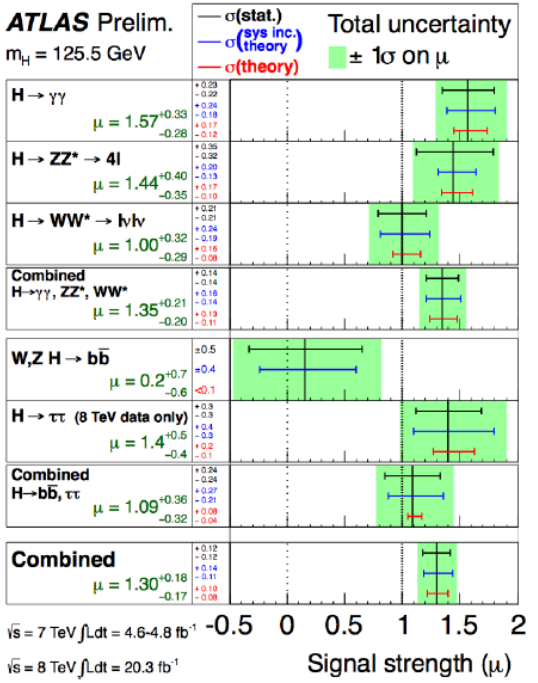
$$\mu_{A\to h}^{h\to B} = \frac{\sigma_{A\to h}}{\sigma_{A\to h}^{SM}} \frac{\mathcal{B}_{h\to B}}{\mathcal{B}_{h\to B}^{SM}}$$



- Large modifications of the Higgs couplings to light quarks
  - h->bb: search channel at the LHC, dominates the total Higgs decay width in the SM
  - Other decays mainly constrained from the total Higgs decay width

Impact of the existing LHC Higgs data

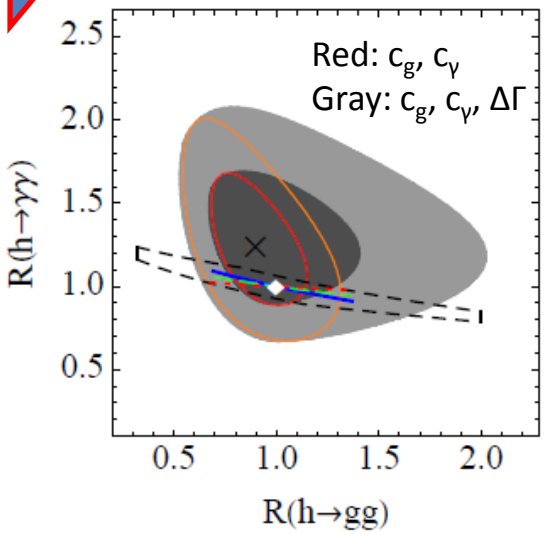


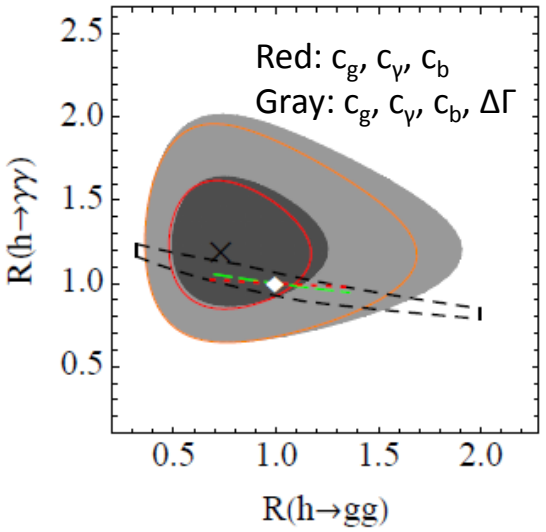


- Loop induced Higgs decays
  - Correlation in h → γ γ and gg → h

$$R_{gg} \equiv \frac{\Gamma_{h\to gg}}{\Gamma^{SM}_{h\to gg}} \simeq \frac{\left|\sum_i y_{ii}\frac{v}{m_i}C(r_i)F_{1/2}(\tau_i)\right|^2}{\left|\frac{1}{2}F_{1/2}(\tau_t)+\frac{1}{2}F_{1/2}(\tau_b)\right|^2},$$

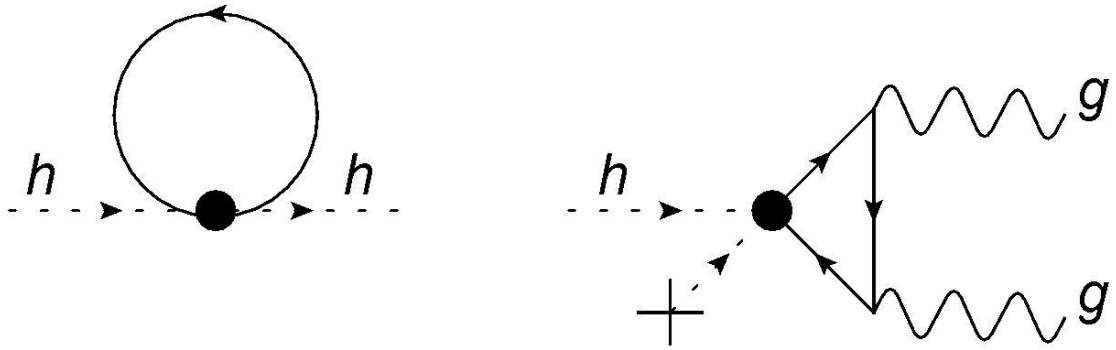
$$R_{\gamma\gamma} \equiv \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}} \simeq \frac{\left|F_1(\tau_W)+\sum_i y_{ii}\frac{v}{m_i}d(r_i)Q_i^2F_{1/2}(\tau_i)\right|^2}{\left|F_1(\tau_W)+\frac{4}{3}F_{1/2}(\tau_t)\right|^2},$$





Singlet up-like VLQ: Naturalness and Higgs data

$H^\dagger H \overline{Q} Q$



- Loop induced Higgs decays

$$R_{gg} = \frac{|0.68 r_y - 0.040|^2 + 0.057^2}{0.65^2} \qquad R_{\gamma\gamma} = \frac{|-8.3 + 1.8 r_y|^2}{|-6.5|^2}$$

- Naturalness criteria $r_y = 1 - \dfrac{m_t^2}{m_{u'}^2}$
- From the Higgs data fit: $m_{u'} > 400$ GeV
- Complementary to direct searches

Conclusions

- We study the impact of VLQs on Higgs physics
- Within renormalizable models Higgs properties remain SM-like
- Leading dimension five operators impact the LHC Higgs data

Coupling	Constraint
$\lvert X^{u'}_{uc,cu}\rvert v/\Lambda$	$< 7 \times 10^{-5}$
$\sqrt{\lvert X^{u'}_{tu,tc}\rvert^2 + \lvert X^{u'}_{ut,ct}\rvert^2} v/\Lambda$	< 0.34
$\lvert X^{d'}_{sd,ds}\rvert v/\Lambda$	$< 2 \times 10^{-5}$
$\lvert X^{d'}_{bd,db}\rvert v/\Lambda$	$< 2 \times 10^{-4}$
$\lvert X^{d'}_{sb,bs}\rvert v/\Lambda$	$< 1 \times 10^{-3}$
$\sqrt{\lvert X^{u'}_{uu}\rvert^2 + \lvert X^{u'}_{cc}\rvert^2} v/\Lambda$	< 0.022
$\sqrt{\lvert X^{d'}_{dd}\rvert^2 + \lvert X^{d'}_{ss}\rvert^2} v/\Lambda$	< 0.027
$\sqrt{\lvert X^{u'}_{uu}\rvert^2 + \lvert X^{u'}_{cc}\rvert^2 + \lvert X^{d'}_{dd}\rvert^2 + \lvert X^{d'}_{ss}\rvert^2} v/\Lambda$	< 0.025
$\lvert 0.019 - X^{d'}_{bb} v/\Lambda\rvert$	< 0.038 < 0.036

Existing LHC Higgs data