Vector-Like Quark Phenomenology: From the A_{FB}^{b} and $t\bar{t}H$ Anomalies to the HL-LHC Reach

(Based on 1510.07527)

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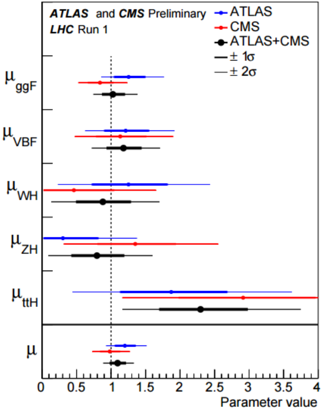
Introduction

- What are Vector-Like Quarks (VLQs) ? Quarks whose left and right-handed chiralities transform the same way under $\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$;
- Gauge-invariant mass term without a Higgs: $M\bar{Q}_L Q_R + \mathrm{h.c.}$;
- Can couple with SM quarks via Yukawa interactions → after EWSB, mixing with SM quarks;
- Common assumption: mixing only with the 3rd generation SM quarks;
- Eigenmasses and couplings obtained by rotating from the interaction basis to the mass basis;
- Examples of VLQs: Kaluza-Klein states in extra-dimensional scenarios, bound states in Composite Higgs theories.

Motivation



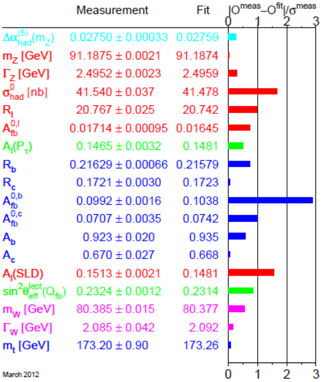


Figure : Higgs production rates [ATLAS-CONF-2015-044] (left) and LEP EW precision results [http://lepewwg.web.cern.ch] (right).

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Towards a Minimal Model: The Bottom Sector

The minimal VLQ field content necessary to explain (i.e. reproduce the experimental result at less than 1σ) A^b_{FB} and $t\bar{t}H$ can be inferred from phenomenological arguments [hep-ph/0109097, 1209.6382]. For the bottom sector:

- The measured values of $A^b_{\rm FB}$ and R_b favor a $\rm SU(2)_L$ VL multiplet containing a bottom-like b' with positive isospin $\rightarrow$ minimal choice is a doublet:

$$B_{L,R} = (b', q_{-4/3}) \sim (3, 2, -5/6).$$

- Doublet is not enough for reproducing the experimental results $\rightarrow$ add also a singlet:

$$b''_{L,R} \sim (3, 1, -1/3).$$

Towards a Minimal Model: The Top Sector

One can repeat the previous exercise for the top sector:

- Adding only one VLQ multiplet containing a top partner cannot explain the $t\bar{t}H$ excess and reproduce the measured top mass of ~ 174 GeV;
- To significantly enhance y_t, one needs VLQs that have Yukawa couplings in the interaction basis with both t_L and $t_R \rightarrow$ minimal choice is adding a VL $\mathrm{SU(2)_L}$ doublet, T, and a singlet, t'' ($T_{L,R} = (t', b')$ disfavored because b' has isospin < 0):

$$T_{L,R} = (q_{5/3}, t') \sim (3, 2, 7/6), \quad t''_{L,R} \sim (3, 1, 2/3).$$

Apart the SM $Q_L = (t, b)_L$, t_R and b_R, the minimal model will contain:

$$T_{L,R},\ t''_{L,R},\ B_{L,R}, \text{ and } b''_{L,R}.$$

The Minimal Model: Numerical Results

$$-\mathcal{L} \supset Y_{t_1}\,\overline{Q}_L\tilde{H}\,t_R + Y_{t_2}\,\overline{Q}_L\tilde{H}\,t''_R + Y_{t_3}\,\overline{T}_LH\,t_R + Y_{t_4}\,\overline{T}_LH\,t''_R + Y_{t_5}\,\overline{T}_RH\,t''_L$$
$$+\, Y_{b_1}\,\overline{Q}_LH\,b_R + Y_{b_2}\,\overline{Q}_LH\,b''_R + Y_{b_3}\,\overline{B}_L\tilde{H}\,b_R + Y_{b_4}\,\overline{B}_L\tilde{H}\,b''_R + Y_{b_5}\,\overline{B}_R\tilde{H}\,b''_L$$
$$+\, m_1\,\overline{T}_LT_R + m_2\,\overline{t}''_Lt''_R + m_3\,\overline{B}_LB_R + m_4\,\overline{b}''_Lb''_R + \text{h.c.}\,.$$

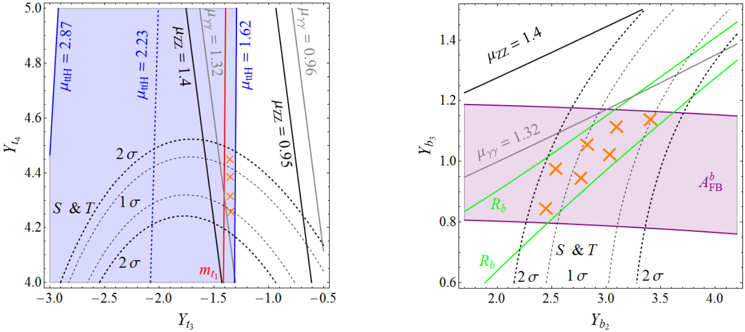


Figure : Top sector (left) and bottom sector (right). In the allowed regions of parameter space, the lightest VLQs have masses of ~ 1 TeV.

Overview

Higgs Decay Ratios at the HL-LHC: $D_{\gamma\gamma}$

In Higgs physics at the (HL-)LHC, production channels are the main source of theoretical uncertainty $\rightarrow$ a promising way of diminishing this error is to consider ratios of Higgs production times decay rates [1208.3436]. A well-motivated example is:

$$D_{\gamma\gamma} \equiv \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H \to ZZ^*)} \simeq \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ^*)}.$$

- $H \to \gamma\gamma$ and $H \to ZZ^*$ precisely measured;
- $D_{\gamma\gamma}$ sensitive especially to VLQs with high electric charge;
- Challenge $\rightarrow$ in such ratios, the same kinematical cuts should be applied when measuring the two processes $\Rightarrow$ in this ideal case, the production cross section cancels (as well as the Higgs total width)! In the following, we will assume that this indeed happens.

VLQ Mass Reach Through $D_{\gamma\gamma}$

In the following, to get an idea of the power of $D_{\gamma\gamma}$ for indirect detection of VLQs, we will focus on simplified, generic VLQ models. Also, we no longer try to explain the $t\bar{t}H$ and A^b_{FB} deviations from the SM.

- We consider 2 VLQ multiplets that mix between themselves, with one of them significantly heavier than the other;
- Set their mixing with SM quarks to 0.

We assume (rather optimistically) that the experimental error at the HL-LHC will be:

$$\frac{\Delta D_{\gamma\gamma}}{D_{\gamma\gamma}} = 1\%,$$

at 68% C.L., with the experimental central value of $D_{\gamma\gamma}$ taken to be equal to its SM value at LO.

VLQ Mass Reach Through $D_{\gamma\gamma}$: Numerical Results

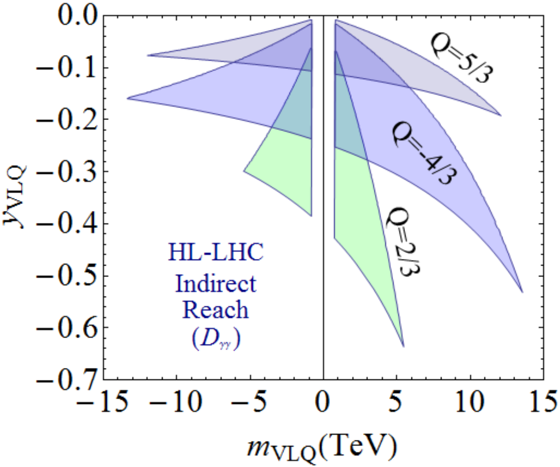


Figure : Mass (m_{VLQ}) vs mass basis Yukawa coupling (y_{VLQ}) of the lighter VL quark. Q stands for electric charge.

VLQ Mass Reach Through D_{bb}

What about bottom-like VLQs? A good way to search indirectly for them is to consider the ratio:

$$D_{bb} \equiv \frac{\sigma(pp \to VH \to Vb\bar{b})}{\sigma(pp \to VH \to VZZ^*)} \simeq \frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to ZZ^*)}.$$

Again, we study a generic model where only one bottom-like VLQ singlet mixes with the SM-like b quark. We assume that, at 68% C.L., the HL-LHC experimental error will be:

$$\frac{\Delta D_{bb}}{D_{bb}} = 5\%,$$

with the experimental central value taken equal to its SM value at LO.

VLQ Mass Reach Through D_{bb}: Numerical Results

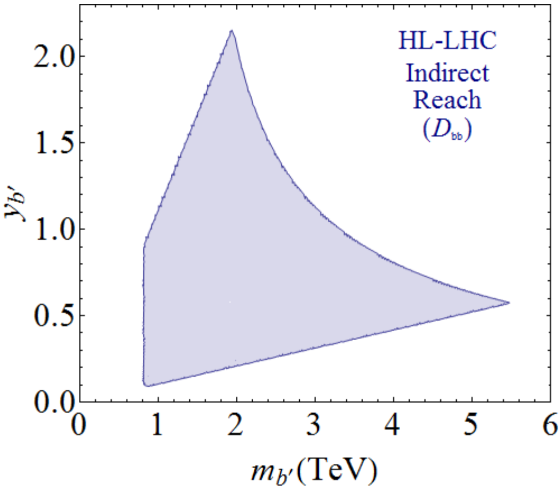


Figure : Mass vs mass basis Yukawa coupling of the b' VLQ.

Overview

Conclusions

- By adding VLQ multiplets to the SM, the present experimental anomalies in the heavy quark sector ($A_{\rm FB}^b$ and $t\bar{t}H$) can be explained, while satisfying the constraints coming from EWPT at LEP and from Higgs physics at the LHC.

- Interestingly, the obtained VLQ model predicts top, bottom and exotic VL partners with masses typically at the TeV scale, which can be searched for at Run 2 of the LHC.

- By considering ratios of Higgs production times decay rates, we showed that top and bottom VL partners with masses up to 5 TeV and more exotic VLQs with masses in the 10 TeV range can be indirectly probed at the HL-LHC. This is to be compared with the mass reach through direct searches, which is estimated to be around 1.5 – 2 TeV [1307.7135].

Backup: $H \to \gamma\gamma$ Formulas

$$\Gamma(H \to \gamma\gamma) \propto \left| A_1(\tau_W) + N_c \sum_f Q_f^2 \sum_i \left(\frac{y_i}{m_i} A_{1/2}(\tau_i) \right)_f \right|^2 .$$

Example: top quark plus top-like VLQs:

$$\sum_i \left(\frac{y_i}{m_i} A_{1/2}(\tau_i) \right)_t \simeq \frac{4}{3} \sum_i \left(\frac{y_i}{m_i} \right)_t = \frac{4}{3} \operatorname{tr} \left(\mathcal{M}_t^{-1} \frac{\partial \mathcal{M}_t}{\partial v} \right)$$
$$= \frac{4}{3} \partial_v \left(\log \det \mathcal{M}_t \right) .$$

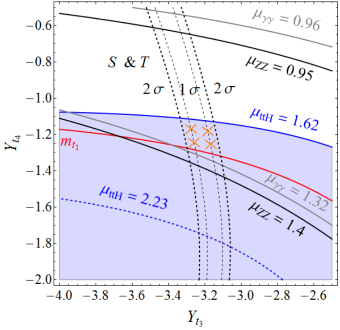
If there is only one extra top-like VLQ:

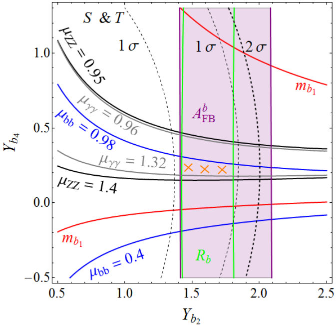
$$\mathcal{M}_t = \frac{1}{\sqrt{2}} \begin{pmatrix} vY_{t_1} & vY_{t_2} \\ 0 & \sqrt{2}m \end{pmatrix} \Rightarrow \partial_v \left(\log \det \mathcal{M}_t \right) = \frac{1}{v} = \left(\frac{y_t}{m_t} \right)_{\text{SM}} .$$

Backup: Model B

Model **B** = Model **A** with the replacement

$$b'' \to X_{L,R} = (t''', b'', q'_{-4/3}) \sim (3, 3, -1/3).$$





Backup: Model C

Model **C** = Model **A** with the addition of:

$$Z_{L,R} = (q_{8/3}, q_{5/3}, t''') \sim (3, 3, 5/3).$$