A universally enhanced light-quarks Yukawa couplings paradigm

Shaouly Bar-Shalom\textsuperscript{1} and Amarjit Soni\textsuperscript{2}

\textsuperscript{1}Physics Department, Technion-Institute of Technology, Haifa 32000, Israel
\textsuperscript{2}Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

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We propose that natural TeV-scale new physics (NP) with $O(1)$ couplings to the standard model (SM) quarks may lead to a universal enhancement of the Yukawa couplings of all the light quarks, perhaps to a size comparable to that of the SM b-quark Yukawa coupling, i.e., $y_b \sim O(y_b^{SM})$ for $q = u, d, c, s$. This scenario is described within an effective field theory (EFT) extension of the SM, where a potential contribution of certain dimension six effective operators to the light quarks Yukawa couplings is $y_q \sim O\left(\frac{f}{\Lambda} \right)$, where $v$ is the Higgs vacuum expectation value (VEV) $v = 246$ GeV, $\Lambda$ is the typical scale of the underlying heavy NP and $f$ depends on its properties and details. For example, with $\Lambda \sim 1.5$ TeV and natural NP couplings $f \sim O(1)$, one obtains $y_q \sim 0.025 \sim y_b^{SM}$. We also explore this enhanced light quarks Yukawa paradigm in extensions of the SM which contain TeV-scale vector-like quarks and we match them to the specific higher dimensional effective operators in the EFT description. We discuss the constraints on this scenario and the flavor structure of the underlying NP dynamics and suggest some resulting “smoking gun” signals that should be searched for at the LHC, such as multi-Higgs production $pp \rightarrow hh, hhH$ and single Higgs production in association with a high $p_T$ jet $(j)$ or photon $pp \rightarrow hj, h\gamma$ and with a single top-quark $pp \rightarrow ht$.

I. INTRODUCTION

After the discovery of the 125 GeV Higgs-like boson, one of the main tasks of the current and future runs of the LHC is to uncover its properties and the physics which underlies its origin. This has led to considerable effort from both the theoretical and experimental sides, in the hunt for the NP, that may address fundamental questions in particle physics, possibly related to the scalar sector of the SM, e.g., the observed hierarchy between the two disparate Planck and EW scales and the flavor and CP structure in the fermion sector.

The Higgs mechanism of the SM suggests that the fermion’s Yukawa couplings are proportional to the ratio between their masses and the Higgs VEV $(v$ = 246 GeV), i.e., $y_f \propto m_f/v$. In particular, for the light fermions, where $m_f/v \ll 1$, reactions involving their interaction with the Higgs boson are, in many cases, expected to be vanishingly small and unobservable in the SM. Therefore, any observable signal which can be associated with an enhanced Yukawa coupling of a light fermion would stand out as clear evidence for NP beyond the SM. Indeed, current experimental bounds and Higgs measurements do not exclude the possibility that the Yukawa sector of the SM is modified by TeV-scale NP that directly effect the couplings of the observed 125 GeV Higgs; the current bounds do not exclude Yukawa couplings of the Higgs to the light quarks of the order of the b-quark Yukawa coupling, i.e., allowing $y_q \sim O(y_b^{SM})$ for $q = d, u, s, c$ \cite{1}\cite{6}.

In this work we propose a framework where the Yukawa interactions of all the light quarks are universally enhanced, naming it the “Universally Enhanced Higgs Yukawa” paradigm - UEHiggsY paradigm. In particular, we suggest that, if the pattern and size of the Higgs Yukawa interaction Lagrangian is controlled by some TeV-scale underlying NP with natural couplings of $O(1)$, then $y_q \sim O(y_b^{SM})$ can be universally realized for all $q = d, u, s, c, b$. We first describe the UEHiggsY paradigm based on an EFT approach and then give an explicit implementation of this mechanism within a renormalizable prescription involving new TeV-scale vector-like quarks (VLQ) with natural $O(1)$ Yukawa-like couplings to the SM quarks.

II. AN EFT DESCRIPTION OF THE UEHIGGSY PARADIGM

Consider the effective Lagrangian piece corresponding to one of the simplest dimension six effective operators that can generate non-SM Yukawa-like terms:

$$\Delta \mathcal{L}_{qH} = \frac{H^\dagger H}{\Lambda^2} \cdot \left( f u_h q_L H u_R + f d_h q_L H d_R \right) + h.c. , (1)$$

where $H$ ($\bar{H} \equiv i\tau_2 H^*$), $q_L$ and $u_R, d_R$ are the SU(2) SM Higgs, left-handed quark doublets and right-handed quark singlets, respectively. Also, $\Lambda$ is the NP scale and $f_i$ are the corresponding Wilson coefficients which depend on the details of the underlying NP theory.

When the above dim.6 operators are added to the SM Yukawa interaction Lagrangian:

$$\mathcal{L}_{SM}^Y = -Y_u q_L H u_R - Y_d q_L H d_R + h.c. , (2)$$

and EW symmetry is spontaneously broken, one obtains the quark mass matrices $M_q$ ($q = u, d$ for up and down-quarks, respectively) and the Yukawa couplings in the weak basis. The physical quark masses, $M_q$, are then

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\textsuperscript{1}Electronic address: shaouly@physics.technion.ac.il
\textsuperscript{2}Electronic address: adlersoni@gmail.com
obtained by unitary rotations of both the left and right-handed quark fields to the quarks mass basis, $q_{LR} \rightarrow S_{L,R}^q q_{L,R}$ (the CKM matrix is $V = S_L^u S_L^d$): $M_d = S_d^d M_d S_R^d = \text{diag}(m_d, m_s, m_b)$ and $M_u = S_u^u M_u S_R^u = \text{diag}(m_u, m_c, m_t)$, where:

$$M_q = \frac{v}{\sqrt{2}} \left( \hat{Y}_d - \frac{1}{2} \hat{\epsilon}_q \hat{q}_H \right) ; \; \epsilon = \frac{v^2}{\Lambda^2} ,$$

and couplings in the physical quark mass basis are denoted with a hat: $\hat{Y}_q = (S_L^q)^T Y_q S_R^q$ and $\hat{f}_{qH} = (S_L^q)^T f_{qH} S_R^q$.

The Yukawa couplings, $y_q^\text{ij} \bar{q}_i q_j h$, are then given by:

$$y_q^\text{ij} = \frac{m_q}{v} \delta_{ij} - \frac{\epsilon}{\sqrt{2}} \left( \hat{f}_{qH}^\text{ij} R + \hat{\epsilon} \hat{q}_H^\text{ij} L \right) ,$$

where $m_q$ is the physical quark mass and $R(L) = (1 + (-) \gamma_5)/2$.

It is, therefore, evident from Eq. [4] that our UEHiggsY paradigm is realized if the NP operators in Eq. [1] are natural, i.e., if $\hat{f}_{qH} \sim \mathcal{O}(1)$, and have a typical scale of $\Lambda \sim \mathcal{O}(1 \text{ TeV})$. More specifically, taking $\Lambda \sim 1.3$ TeV and $\hat{f}_{qH} \propto f_{qH} \sim \mathcal{O}(1)$, we have $\epsilon f_{qH} \sim 0.035$, thus leading to the UEHiggsY scenario:

$$y_q \sim \epsilon \hat{f}_{qH} \sim 0.025 \sim \hat{y}_q^\text{SM} ,$$

for all the light quarks ($q = d, u, s, c$) where $m_q/v \ll \epsilon \hat{f}_{qH}$, as well as for the b-quark for which $m_b/v \sim \epsilon \hat{f}_{qH}$.

In addition to the modification of the light quark Yukawa couplings, the effective operators in Eq. [1] also generates new tree-level contact interactions between the SM light quarks and two or three Higgs particles, $q \bar{q} h h$ and $q q hh h$. These new couplings are also proportional to $\hat{f}_{qH}$:

$$\Gamma_{q_i q_j hh} = \frac{3\epsilon}{\sqrt{2}v} \left( \hat{f}_{qH}^\text{ij} R + \hat{\epsilon} \hat{q}_H^\text{ij} L \right) , \; \Gamma_{q_i q_j hh h} = \frac{\Gamma_{q_i q_j hh}}{v} .$$

and may cause large deviations (from the expected SM rates) to the multi-Higgs production channels $pp \rightarrow hh, hh h$ at the LHC, as will be discussed in section [V].

The above UEHiggsY paradigm suffers, however, from two potential problems associated with fine-tuning and flavor:

**Fine-tuning:** Some degree of fine-tuning is required among the parameters of the Lagrangian pieces $L^\text{SM}_Y + \Delta L_{qH}$ in order to simultaneously accommodate the light-quark masses $m_q \ll m_b$ and the enhanced Yukawa couplings of $y_q \sim \mathcal{O}(\hat{y}_q^\text{SM})$. As will be discussed below, this fine-tuning is, however, not worse than the flavor fine-tuning in the SM.

**Flavor:** The Yukawa couplings $Y_q$ and Wilson coefficients $\hat{f}_{qH}$ cannot be diagonalized simultaneously in general. As a result, flavor changing neutral couplings (FCNC) among the SM quarks may appear. This is manifested by the off-diagonal elements of $\hat{f}_{qH}$ (see Eq. [4]), which are a-priori expected to be of $\mathcal{O}(1)$. In particular, with $\Lambda \sim \mathcal{O}(1 \text{ TeV})$, we obtain FCNC $q_i q_j h$ couplings also of the size of the b-quark Yukawa, e.g., $y_{q_b}^{12} \sim \epsilon f_{qH}/\sqrt{2} \sim \mathcal{O}(\hat{y}_b^\text{SM})$ (see Eq. [5]). We will address this flavor problem in the next section.

As for the fine-tuning issue, it is typically of the order of $m_q/m_b$, so that the worst fine-tuning corresponds to the 1st generation quarks, where it is $\sim \mathcal{O}(m_u,d/m_b) \sim 10^{-3}$. To see that, consider the mass and Yukawa coupling of a single light quark $q$ in the presence of the interactions terms in $L^\text{SM}_Y + \Delta L_{qH}$:

$$m_q = \frac{v}{\sqrt{2}} \left( Y_q - \frac{1}{2} \hat{\epsilon} f_{qH} \right) , \quad y_q = \frac{1}{\sqrt{2}} \left( Y_q - \frac{3}{2} \epsilon f_{qH} \right) .$$

In particular, fixing $m_q$ to its measured/observed value (e.g., $m_q \sim 2$ MeV for the u-quark) and requiring that $y_q \sim y_q^\text{SM} = \sqrt{2}m_b/v \sim 0.025$, the solution to Eqs. [7] and [8] for the corresponding couplings $Y_q$ and $f_{qH}$ is:

$$Y_q = -\frac{y_q^\text{SM}}{\sqrt{2}} \left( 1 - \frac{3}{\sqrt{2}} \frac{m_q}{m_b} \right) , \quad \epsilon f_{qH} = -\sqrt{2} y_q^\text{SM} \left( 1 - \frac{1}{\sqrt{2}} \frac{m_q}{m_b} \right) .$$

Thus, both $\epsilon f_{qh}$ and $Y_q$ need to be of $\mathcal{O}(y_q^\text{SM})$ and the resulting fine-tuning is at the level of $\Delta q \sim \mathcal{O}(m_q/m_b)$. We therefore see that the UEHiggsY paradigm which arises from natural TeV-scale NP with $\mathcal{O}(1)$ couplings, requires technical fine-tuning of the quark-Higgs interaction parameters at the level of $\Delta q \sim \mathcal{O}(0.1, 0.01, 0.001)$ for $q = c, s, u/d$, respectively. In particular, the fine-tuning is at most at the per-mill level and is only technical in the sense that the fine-tuned parameters, once fixed, are stable against higher-order corrections (as opposed to the fine-tuning in the SM Higgs potential). In fact, this technical $10^{-3} - 10^{-1}$ fine-tuning is comparable to the flavor fine-tuning problem in the SM, which is manifest in the CKM matrix that has no a-priori reason to be close to the identity matrix $[7]$.

III. THE UNDERLYING HEAVY PHYSICS AND FLAVOR

The effective operators in Eq. [1] can be generated by various types of heavy underlying NP which contain new heavy particles that couple to the SM fermions. In Fig. 1 we depict examples of tree-level diagrams in the underlying theory, which can generate the dim. 6 effective operators of Eq. [1] when the heavy fields are integrated
In particular, the underlying NP theory may contain heavy VLQ ($F_1$ and $F_2$) and/or a heavy scalar ($\Phi$) - both have the required quantum numbers to couple to the SM quarks and Higgs fields. Indeed, new heavy scalars and/or vector-like fermions are elementary building blocks of several well motivated beyond the SM scenarios which may address fundamental unresolved theoretical questions in particle physics.

As an example for a simple occurrence of the UEHiggsY framework, we will focus below on the heavy VLQ scenario, which has rich phenomenological implications and may be linked to the mechanism responsible for solving the hierarchy problem, as well as to naturalness issues in supersymmetry and in strongly coupled theories where the light Higgs boson is considered to be a pseudo-Nambu-Goldstone boson of an underlying broken global symmetry, e.g., in little Higgs models and in models with partial compositeness.

VLQ dynamics may also be important ingredient of the UV completion of the SM, and in particular of the above VLQ scenario, should have a mechanism which strongly suppresses or forbids the above Higgs mediated FC couplings to the SM quarks and their physical mass basis.

With this setup, diagram (a) in Fig. 1 generates the following 3×3 Wilson coefficients/matrices $f_{sH}$, $\hat{f}_{dH}$ (i.e., in the physical quark mass basis) and effective scales of the operators in Eq. 1:

$$f_{sH} = \hat{\lambda}_{Uq} \hat{\lambda}_{QD}^\dagger \hat{\lambda}_{Qd}, \quad \Lambda = \sqrt{M_U M_D},$$

$$\hat{f}_{dH} = \hat{\lambda}_{Dq} \hat{\lambda}_{QD}^\dagger \hat{\lambda}_{Qd}, \quad \Lambda = \sqrt{M_D M_Q}.$$  

Thus, if the VLQ have a mass $M \sim M_U \sim M_D \sim M_Q \sim 1.5$ TeV and natural couplings $\hat{\lambda}_i \sim O(1)$ (so that $f_{sH} \sim O(1)$), then the Yukawa couplings of all light quarks are universally enhanced, with a typical size of (see Eq. 5):

$$y_u^{ij} \sim \frac{v^2}{M^2} \left( \hat{\lambda}_{Uq} \hat{\lambda}_{QU}^\dagger \hat{\lambda}_{Qd} \right)^{ij} \frac{M_{1-5 \text{ TeV}}}{\hat{\lambda}_{ij}^{b(1)}} \frac{y_b^{SM}}{y_b^{SM}},$$

$$y_d^{ij} \sim \frac{v^2}{M^2} \left( \hat{\lambda}_{Dq} \hat{\lambda}_{QD}^\dagger \hat{\lambda}_{Qd} \right)^{ij} \frac{M_{1-5 \text{ TeV}}}{\hat{\lambda}_{ij}^{b(1)}} \frac{y_b^{SM}}{y_b^{SM}},$$

therefore, also generating potentially “dangerous” FCNC $q_i q_j h$ transitions of the same size, i.e., $y_q^{ij} \sim O(y_b^{SM})$ for $i \neq j$.

Indeed, FCNC in the down quark sector and among the 1st and 2nd generations of the up quark sector are severely constrained by experiment - to the level of $12^{21} < 10^{-5}$, $13,31,23,32 < 10^{-4}$, $12^{21} < 10^{-5}$. This puts stringent constraints on the off-diagonal elements of the Wilson coefficients $f_{sH}$. In particular, for $\Lambda \sim O(1)$ TeV, these bounds correspond to $\hat{f}_{ij}^{sH} \lesssim 10^{-3} - 10^{-4}$ for $i \neq j$ and $\hat{f}_{ij}^{12,21} \lesssim 10^{-4}$, which therefore, constrain the corresponding flavor changing VLQ coupling to the SM quarks. This observed smallness of FCNC $q_i \rightarrow q_j$ transitions is a strong indication that any viable underlying UV completion of the SM, and in particular of the above VLQ scenario, should have a mechanism which strongly suppresses or forbids the above Higgs mediated FC couplings. Such a mechanism is often assumed to be linked to an underlying flavor symmetry which gives flavor selection rules, thus imposing specific flavor textures on the FCNC couplings.

There are several types of mechanisms and/or flavor symmetries that can be applied to our VLQ framework, that will give the desired flavor selection rules. Here we wish to consider simple and rather minimal examples of flavor symmetries which are consistent with both

![Fig. 1: Tree-level diagrams in the underlying heavy theory which can generate the dimension 6 operators in Eq. 1, involving exchanges of heavy VLQ $F_1, F_2$ (left) and a heavy scalar $\Phi$ (right). See also text.](image-url)
coefficients \( \hat{Z} \) assignments for the fermion fields in their mass basis. Our notation for the charge assignments is \( \alpha \) and \( 10 \) for the diagonal entries of \( \hat{Z} \). Furthermore, with the UEHiggsY setup of Eqs. 9 and 10 for the diagonal entries of \( \hat{Z} \) and \( \hat{f}_{uH} \) yielding non-diagonal structures (textures) for some of the Yukawa-like couplings and Wilson coefficients. In particular, with the UEHiggsY framework. In particular, we introduce the current experimental constraints on FCNC and with our UEHiggsY framework. In particular, we introduce a \( Z_3 \) flavor symmetry under which the physical states (i.e., mass eigenstates) of the SM quarks and VLQ fields transform as \( \psi^k \rightarrow e^{i\alpha(k)\tau_3} \psi \), where \( \tau_3 \equiv 2\pi/3 \), \( k \) is the generation index, \( \psi \equiv q_L, u_R, d_R, Q_L, U_R, D_R \) and \( \alpha(k) \) are the \( Z_3 \) charges of \( \psi^k \).

The simplest \( Z_3 \) setup, which has no tree-level FCNC and also accommodates the UEHiggsY paradigm is the choice \( \alpha(k) = k \). In this case, all the Yukawa-like couplings involving the VLQ, i.e., \( \hat{Y} \) in Eqs. [1] and [2] as well as the SM Yukawa couplings \( \hat{Y}_{u,d} \) are diagonal, so that the Wilson coefficients \( \hat{f}_{uH} \) and \( \hat{f}_{uH} \) are also diagonal, giving \( y_{\psi} \sim y_{\psi}^{SM} \delta_{ij} \) for \( q = u, d, c, s, b \) and no tree-level FCNC. Furthermore, with the UEHiggsY setup of Eqs. [2] and [10] for the diagonal entries of \( \hat{Y} \) and \( \hat{f}_{uH} \):

\[
\hat{Y}_{\psi} = -y_{\psi}^{SM} \frac{1 - \frac{3}{\sqrt{2}} \frac{m_u}{m_b}}{\sqrt{2}} \],
\[
\hat{f}_{uH} = -\frac{y_{\psi}^{SM}}{\epsilon} \frac{1 - \frac{1}{\sqrt{2}} \frac{m_u}{m_b}}{\sqrt{2}} \],
\]

the \( Z_3 \) symmetry with \( \alpha(k) = k \) reproduces the desired quark mass spectrum.

In Table I, we list three additional examples of \( Z_3 \) symmetries which correspond to different charge assignments to the fermion fields and yield non-diagonal structures (textures) for some of the Yukawa-like couplings and Wilson coefficients. In particular, with the \( Z_3 \) symmetries 1 and 2 the SM Yukawa couplings \( \hat{Y}_{u,d} \) as well as Wilson coefficients \( \hat{f}_{uH,dH} \) are diagonal and \( \hat{f}_{uH,dH} = 0 \). Thus, these two flavor symmetries with the \( Y_u^{11,22} \) and \( f_{uH,dH} \) entries of Eqs. [17] and [18] and with \( Y_3^{33} = \sqrt{2} m_t/v \) and \( Y_3^{33} = \sqrt{2} m_b/v \), will bring about the UEHiggsY scenario with no tree-level FCNC.

The third \( Z_3 \) symmetry in Table II generates a tree-level \( u_{LH} \) FCNC coupling (i.e., due to \( f_{uH}^{13} \neq 0 \)), which is not well constrained and which may yield an interesting signal of exclusive production of the Higgs boson in association with a single top-quark at the LHC. This effect will be discussed in more detail in section V.1. Notice also that, while the flavor structures of the SM Yukawa coupling and Wilson coefficients in the down-quark sector are similar in all the three \( Z_3 \) symmetries, the up-quark sector corresponding to the third \( Z_3 \) symmetry has a rank 2 mass matrix, requiring \( \epsilon f_{uH}^{13} = 2 \hat{Y}_{u}^{13} \) in order to have a diagonal up-quark mass matrix (i.e., \( M_u^{13} = 0 \)). Thus,
We neglect Higgs production via $pp \to H$ and $pp \to hW, hZ$ followed by the decays $h \to \gamma\gamma, WW^*, ZZ^*, \tau\tau$ and $h \to bb$, as analysed by the ATLAS and CMS collaborations [27,31]. In the SM, the s-channel production of the 125 GeV Higgs is dominated by the gluon-fusion production mechanism $gg \to h$. In particular, the SM tree-level $qq$-fusion production channel, $q\bar{q} \to h$, is negligible due to the vanishingly small light-quarks SM Yukawa couplings (the effect of the light quarks in the 1-loop $ggH$ coupling is also negligible for our purpose, i.e., at most of $O$(few %) for the b-quark [6,28]). In the $pp \to Vh$ channels ($V = W, Z$), the SM rate is dominated by the s-channel $V$ exchange $q\bar{q} \to V^* \to Vh$.

A different picture arises in our UEHiggsY framework, where the Higgs Yukawa couplings to all the light quarks are universally modified/enhanced. Higgs production via $qq$-fusion becomes important, in particular, the tree-level processes $q\bar{q} \to h$ and $t$-channel $Vh$ production $q\bar{q} \to Vh$ (see diagram for $q\bar{q} \to \gamma h$ in Fig. 2 and replace $\gamma \to V, V = Z$ or $W$). To study the effect of these new $qq$-fusion Higgs production channels, we define Yukawa coupling modifiers, $\kappa_q$, and scale them with the SM b-quark Yukawa, as follows:

$$\kappa_q \equiv \frac{g_q}{g_b} , \quad q = d, u, s, c, b ,$$

so that, in the SM, we have $\kappa_b = 1$, $\kappa_c \sim 0.3$, $\kappa_s \sim O(10^{-2})$ and $\kappa_{u,d} \sim O(10^{-3})$. On the other hand, in the UEHiggsY paradigm with a NP scale $\Lambda \sim O(1 \text{ TeV})$ and $O(1)$ couplings of the heavy states to the SM particles, we expect $\kappa_q \sim O(1)$ for all $q = d, u, s, c, b$ (see Eq. 5), in which case the tree-level $q\bar{q} \to h$ and $h \to q\bar{q}$ production and decay channels also contribute to the signal strength factors $\mu_i$ and $\mu_f$ defined in Eqs. 20 and 21. In particular, in the UEHiggsY setup we have:

$$\mu_i^{UEHiggsY} = \frac{\sigma(gg \to h)_{SM} + \sigma(q\bar{q} \to h)_{UEHiggsY}}{\sigma(gg \to h)_{SM}} = 1 + \sum_q \kappa_q^2 R_q ,$$

where $\kappa_f = \frac{g_{ff}}{g_{bH}} \frac{M_{SM}}{M_f}$ are the couplings modifiers of any of the $hff$ Higgs decay vertices, $R_q$ is defined by

$$R_q \equiv \frac{\sigma(q\bar{q} \to h)_{UEHiggsY}}{\sigma(gg \to h)_{SM}} ,$$

and it is understood that $\sigma(q\bar{q}, gg \to h)$ are convoluted with the corresponding PDF weights and that $\sigma(q\bar{q} \to h)_{UEHiggsY}$ are calculated at tree-level with the values $\kappa_q = 1$ for all light flavors $q = u, d, c, s$ (we neglect here the $bb$-fusion production channel $bb \to h$, which is much smaller than the light quark $q\bar{q} \to h$-fusion channels for $\kappa_b \sim O(1)$, i.e., close to its SM value.

We have calculated the cross-sections $\sigma(q\bar{q} \to h)$ using MadGraph5 [35] at LO parton-level, where a dedicated universal FeynRules output (UFO) model for the UEHiggsY framework was produced for the MadGraph5 sessions using FeynRules [36]. We used the MadGraph5 default PDF set and dynamical scale choice for the central value of the factorization ($\mu_F$) and renormalization ($\mu_R$) scales. We find $\sigma(\mu\bar{u}, dd, ss, c\bar{c}) \approx 33.7, 23.8, 5.4, 4.0$ [pb] at the 13 TeV LHC, so that using the N3LO QCD prediction (at the 13 TeV LHC) $\sigma(gg \to h) \approx 48.6$ [pb] [33], we obtain $\sum_q R_q \sim 1.4$ and, therefore:

$$\mu_{i=gg+qq}^{UEHiggsY} = 1 + \kappa_q^2 \sum_q R_q \sim 1 + 1.4 \kappa_q^2 ,$$

in this case there are only two non-zero mass eigenvalues

in the up-quark sector, so that the UV completion of the VLQ scenario should have another mechanism for generating the top-quark mass, e.g., by coupling the top-quark to another scalar doublet.

IV. CONSTRAINTS FROM THE 125 GEV HIGGS SIGNALS

The measured signals of the 125 GeV Higgs-like particle are sensitive to a variety of new physics scenarios, which may alter the Higgs couplings to the known SM particles involved in its production and decay channels. In particular, modifications of the Higgs Yukawa couplings to the light fermions may lead in general to deviations in both Higgs production and decays.

To see that, we will use the Higgs “signal strength” parameters, which are defined as the ratio between the Higgs production and decay rates and their SM expectations:

$$\mu_i = \frac{\sigma(i \to h \to f)}{\sigma(i \to h \to f)_{SM}} \equiv \mu_i \cdot \mu_f ,$$

with (in the narrow Higgs width approximation):

$$\mu_i = \frac{\sigma(i \to h)}{\sigma(i \to h)_{SM}} ,$$

$$\mu_f = \frac{\Gamma(h \to f)/\Gamma_{SM}}{\Gamma(h \to f))/\Gamma_{SM}} ,$$

where $\Gamma^h(\Gamma^h_{SM})$ are the total width of the 125 GeV Higgs(SM Higgs), $i$ represents the parton content in the proton which is involved the production mechanism and $f$ is the Higgs decay final state.

We will consider the signal strength parameters associated with the production processes $pp \to h$ and $pp \to hW, hZ$ followed by the decays $h \to \gamma\gamma, WW^*, ZZ^*, \tau\tau$ and $h \to bb$, as analysed by the ATLAS and CMS collaborations [27,31]. In the SM, the s-channel production of the 125 GeV Higgs is dominated by the gluon-fusion production mechanism $gg \to h$. In particular, the SM tree-level $qq$-fusion production channel, $q\bar{q} \to h$, is negligible due to the vanishingly small light-quarks SM Yukawa couplings (the effect of the light quarks in the 1-loop $ggH$ coupling is also negligible for our purpose, i.e., at most of $O$(few %) for the b-quark [6,28]). In the $pp \to Vh$ channels ($V = W, Z$), the SM rate is dominated by the s-channel $V$ exchange $q\bar{q} \to V^* \to Vh$.

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where we have added a common K-factor, $K_q$, to the tree-level calculated cross-sections $\sigma(q\bar{q} \rightarrow h)_{UEHiggsY}$. In particular, with $K_q \sim 1.5$ (see e.g., [24]) and the UE-HiggsY values $\kappa_q = 1$ for all $q = u, d, c, s$, we find that $\mu_{q=q\bar{q} \rightarrow h}^{UEHiggsY} \sim 3$, so that the 125 GeV Higgs production mechanism is enhanced in the UEHiggsY framework by a factor of $O(3)$ with respect to the SM expectation.

Turning now to the Higgs decay channels $h \rightarrow \gamma\gamma, ZZ, WW, bb, \tau\tau\tau$ and assuming no new physics in the decay (by setting $\kappa_f = 1$ for $f = \gamma, Z, W, b, \tau$), we obtain from Eq. 24

$$\mu_{hWb,\tau}^{\gamma, Z, W, b, \tau} = \mu_{UEHiggsY}^{\gamma, Z, W, b, \tau} \mu_{UEHiggsY}^{hWb,\tau} \approx \frac{1}{1 + 4\kappa_q^2 BR(h \rightarrow bb)_SM} .$$

Thus, under the UEHiggsY paradigm with $\kappa_q = 1$ we have $\mu_{hWb,\tau}^{\gamma, Z, W, b, \tau} \sim 0.3$, so that the calculated signal strengths of Eq. 19 in these channels are all expected to be the same:

$$\frac{1 + 1.4K_qk^2}{1 + 4\kappa_q^2 BR(h \rightarrow bb)_SM} \rightarrow 0.93 .$$

Indeed, the best measured signal strengths in the four channels $pp \rightarrow h \rightarrow \gamma\gamma, ZZ, WW, \tau\tau\tau$ have a typical 1σ error of 10-20% and, therefore, all consistent with the value $\mu_{hWb,\tau}^{\gamma, Z, W, b, \tau} \sim 0.93$ within $1 - 2\sigma$ (for the LHC RUN1 results see [27] and for updated results from RUN2 see e.g., [29]). In particular, the currently measured 125 GeV Higgs signals in these four channels do not constrain the UEHiggsY paradigm with $\kappa_q = 1$ for all $q = u, d, s, c$.

Let us next consider the UEHiggsY effect on the measured $hV$ production channel followed by $h \rightarrow bb$. This process has currently the best sensitivity to the $h \rightarrow bb$ decay channel and is used to overcome the large QCD background to the simpler $pp \rightarrow h \rightarrow bb$ channel. In particular, in this channel we define $\mu_{pp \rightarrow hV \rightarrow bbV} = R_{hV \rightarrow bbV} = R_{hV} \cdot \mu^*$, with $(V = W, Z)$:

$$R_{hV} = \frac{\sigma(hV)}{\sigma_{SM}(V)} ,$$

where $\sigma_{hV}, \sigma_{SM}(V) \equiv \sigma(pp \rightarrow hW^+ + hW^-), \sigma(pp \rightarrow hZ)$.

As mentioned earlier, in the UEHiggsY framework, the SM s-channel $q\bar{q} \rightarrow V^* \rightarrow hV$ production channels receives additional tree-level contributions from t-channel $q$-exchange diagrams, similar to the one depicted for the process $q\bar{q} \rightarrow h\gamma$ in Fig. 2. In particular, calculating the contribution of these diagrams under the UEHiggsY working assumption with $\kappa_q = 1$ for all $q = u, d, c, s$, we find $R_{hV}^{UEHiggsY} \sim 1.1$ for both $V = W$ and $V = Z$.

Therefore, since $\mu_{hV}^{UEHiggsY} \sim 0.3$ for $\kappa_q = 1$ (see Eq. 27), the UEHiggsY signal strength parameter in the $pp \rightarrow hV \rightarrow bbV$ channel, $R_{hV \rightarrow bbV}$, is expected to be appreciably smaller than one (i.e., than its SM value):

$$R_{hV \rightarrow bbV} = R_{hV}^{UEHiggsY} \cdot \mu_{hV}^{UEHiggsY} \sim 0.33 ,$$

for both the $hW$ and $hZ$ production channels.

It is interesting to note that the RUN1 best fitted value for the measured signal strength in this channel, $pp \rightarrow hV \rightarrow bbV$, was indeed on the lower side and consistent with the above predicted UEHiggsY value $R_{hV \rightarrow bbV} \sim 0.33$ within about $1\sigma$: the combined ATLAS and CMS analysis of RUN1 data yielded $R_{hV \rightarrow bbV} \sim 0.65 \pm 0.3$ [27]. Recent updated ATLAS and CMS analysis in this channel, combining the RUN1 data with about 36 fb$^{-1}$ of RUN2 data at a center of mass energy of 13 TeV yielded higher values $R_{hV \rightarrow bbV} \sim 0.9 \pm 0.3$ [30] and $R_{hV \rightarrow bbV} \sim 1.06 \pm 0.3$ [31], respectively, but the errors in these channels are still large.

We thus conclude that, currently, no significant constraints can be imposed on the UEHiggsY paradigm from the measured 125 GeV Higgs signals. We also note that the Higgs Yukawa couplings to the light quarks can also effect the transverse momentum distributions in Higgs production at the LHC [4, 6, 37]. However, the errors of the currently measured normalized $p_T(h)$ in Higgs + jets production are still relatively large, so that this analysis also cannot yet be used to exclude scenarios with $\kappa_q \sim O(1)$ for the light quarks [4, 5] (see also discussion in the next section).

V. HIGGS SIGNALS OF THE UEHIGGSY PARADIGM

Enhanced light-quark Yukawa couplings may have direct consequences in Higgs production and decay phenomenology at the LHC. Here, we wish to discuss at the exploratory level some of the “smoking gun” signals of the UEHiggsY paradigm, associated with the higher dimension effective operators of Eq. 4.

Let us define the normalized cross-section ratios:

$$R_{F(h)} \equiv \frac{\sigma(pp \rightarrow F(h))}{\sigma(pp \rightarrow F(h))_{SM}} ,$$

where $F(h)$ stands for a final state with at least one Higgs. In particular, apart from the $pp \rightarrow h, hV$ Higgs
production channels discussed in the previous section, the UEHiggsY framework potentially affects other processes which involve one or more Higgs particles in the final state. Below we will consider some of the Higgs final states which have a noticeable tree-level sensitivity to the UEHiggsY paradigm and which are also recognized, in general, as sensitive probes of NP [38]: Higgs pair and triple Higgs productions, Higgs + jets production, Higgs + single top associated production and Higgs production with a single photon, i.e., $F(h) = hh, hhh, h + nj, ht, h\gamma$.\(^2\)

![Sample diagrams for the processes $pp \to hh$, $hhh$, $h + jet, ht, h\gamma$ due to enhanced $qqh$ couplings within the UEHiggsY paradigm.](image)

**FIG. 2:** Sample diagrams for the processes $pp \to hh$, $hhh$, $h +$ jet, $ht$, $h\gamma$ due to enhanced $qqh$ couplings within the UEHiggsY paradigm.

Here also, all cross-sections are calculated at LO parton level, using MadGraph5aMC\_@NLO [35], with default PDF set and dynamical scale choice for the central value of the factorization and renormalization scales. In addition, following the working assumption of the UEHiggsY paradigm, the effective operators in Eq. 1 are assumed to have a typical scale of $\Lambda \sim \mathcal{O}(1)$ TeV and couplings $f_{ij} \sim \mathcal{O}(1)$, so that all cross-sections reported below are calculated with $qqh$ Yukawa couplings comparable to the SM b-quark Yukawa, i.e., $y_{qqh} = y_{b}^{SM}$.

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**A. Multi-Higgs production $pp \to hh$, $hhh$**

Higgs pair production is one of the main targets for NP searches in the Higgs sector at the LHC, primarily due to its sensitivity to the Higgs self-coupling in the Higgs potential and to heavy NP in the loop induced couplings of the Higgs to gluons [14][32]. In the SM this process is initiated at LO by 1-loop gluon-fusion diagrams $gg \to hh$, and the corresponding cross-section is $\sigma(pp \to hh) \sim 15 \text{ fb}$ at LO, where due to the large QCD corrections, it is typically doubled at NLO [38].

In the UEHiggsY framework, there are additional tree-level diagrams induced by the effective operators of Eq. 1, as depicted in Fig. 2. Setting $f_{ij} = \delta_{ij}$ (i.e., assuming only flavor diagonal couplings) and $\Lambda \sim \mathcal{O}(1)$ TeV, we have $y_{q} \sim y_{b}^{SM}$ for the $qqh$ Yukawa coupling (see Eq. 5) and $R_{hhh} \sim 3y_{b}^{SM}/\alpha$ for the $qqhh$ couplings (see Eq. 6).

For this setup we find at LO and for the 13 TeV LHC:

$$R_{h_{hh}} \equiv \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{SM}} \sim 100 \ ,$$

where more than 90% of the enhancement arises from the tree-level diagrams initiated by the $u$ and $d$ quarks. In particular, the total Higgs production cross-section within the UEHiggsY framework with $y_{q} \sim y_{b}^{SM}$ for $q = u, d, c, s, b$ is $\sigma(pp \to hh) \sim 1.5 \text{ pb}$.

The current best bounds on the $hh$ production cross-section at the 13 TeV are $R_{hh,bb\gamma\gamma} \lesssim 19$ in the $hh \to bb\gamma\gamma$ decay channel (obtained by the CMS collaboration, see [13]) and $R_{hh,bb\bb} \lesssim 29$ in the $hh \to bb\bb$ decay channel (obtained by the ATLAS collaboration, see [14]).

As was shown in the previous section, in our UEHiggsY framework with $f_{ij} = \delta_{ij}$ and $\Lambda \sim \mathcal{O}(1)$ TeV (for which $y_{q} \sim y_{b}^{SM}$ for $q = u, d, c, s, b$) the branching ratios for the decays $h \to bb$ and $h \to \gamma\gamma$ are decreased by about a factor of three with respect to the SM: $BR(h \to bb, \gamma\gamma) \sim 0.3BR(h \to bb, \gamma\gamma)_{SM}$ (see Eq. 27) with $\lambda_{v_{h}} = 1$. Therefore, in these channels we obtain in the UEHiggsY framework: $R_{hh,bb\bb} = R_{hh,bb\gamma\gamma} \sim 100 \times (0.3)^2 \sim 10$, which is an order of magnitude larger than the SM rate, but still below the current sensitivity.

For the triple Higgs production channel, $pp \to hh$, the SM cross-section is around $\sigma(pp \to hh) \sim 30 \text{ ab}$ at LO and about twice larger at NLO [38]. In the UEHiggsY framework (see representative diagrams in Fig. 2) we find that $\sigma(pp \to hhh) \sim 10 \text{ fb}$, so that:

$$R_{hhh} \equiv \frac{\sigma(pp \to hhh)}{\sigma(pp \to hhh)_{SM}} \sim 300 \ .$$

Thus, the expected enhancement over the SM signal in the $hh, hhh$ → $bb\bb\bb\bb$ decay channel is again $R_{hh,bb\bb\bb\bb} \sim \mathcal{O}(10)$. However, since in the UEHiggsY case we have $BR(h \to bb) \sim 0.18$, the triple Higgs cross-section in this channels is $\sigma(pp \to hh \to bb\bb\bb\bb) \sim 10 \text{ fb} \cdot 0.18^3 \sim 60 \text{ fb}$, and, therefore, might be difficult to detect even at the HL-LHC with a luminosity of 3000 inverse fb.

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\(^2\) Some of the Higgs signals considered in this section may also be sensitive at 1-loop to modifications of the 3rd generation Yukawa couplings due to the effective operators in Eq. 1, see e.g., [39][22].
B. Higgs + high $p_T$ light-jet production $pp \rightarrow hj$

In general, there is a tree-level SM contribution to the exclusive Higgs + light-jet production, $pp \rightarrow hj$, from the hard processes $qq \rightarrow hj$, $gq \rightarrow hj$ and $qg \rightarrow hj$, where $q = u, d, c$ or $s$. However, since the corresponding tree-level diagrams (e.g., the $t$-channel diagram for $gq \rightarrow hj$ in Fig. 2) are proportional to the light-quarks Yukawa couplings, the effect of these light-quark initiated hard-processes on the overall $pp \rightarrow hj$ cross-section is negligibly small in the SM (i.e., when $y_q \ll 1$ in particular for $q = u, d$). Thus, the dominant SM contribution to the Higgs + light-jet cross-section arises from the 1-loop gluon-fusion process $gg \rightarrow gh$, which, at leading order, is generated mainly by 1-loop top-quark exchanges.

If, on the other hand, $y_q \sim y_q^{SM}$ for all $q = u, d, c, s$, as expected in the UEHiggsY framework, then the contribution (to the $pp \rightarrow hj$ cross-section) from the quark initiated tree-level process $qq \rightarrow hj$, $gq \rightarrow hj$ and $qg \rightarrow hj$ becomes appreciably larger. Indeed, in [37] we have shown that the Higgs $p_T$ distribution in $pp \rightarrow hj$ production at the LHC is a rather sensitive probe of the light-quarks Yukawa couplings (and also of other forms of NP in the Higgs-gluon $hgg$ and quark-gluon $qqg$ interactions) and thus of the UEHiggsY paradigm.

In particular, we have defined in [37] the signal strength for $pp \rightarrow hj$, followed by the Higgs decay $h \rightarrow ff$, where $f$ can be any of the SM Higgs decay products (e.g., $f = b$, $\tau$, $\gamma$, $W$, $Z$):

$$ R_{hj\rightarrow ffj} = \frac{\hat{\sigma}(pp \rightarrow hj \rightarrow ff + j)}{\hat{\sigma}(pp \rightarrow hj \rightarrow ff + j)_{SM}} \approx \frac{\hat{\sigma}(pp \rightarrow hj)}{\hat{\sigma}(pp \rightarrow hj)_{SM}} \frac{BR(h \rightarrow ff)}{BR(h \rightarrow ff)_{SM}}. $$

(34)

where $\hat{\sigma}$ is the $p_T$-dependent “cumulative cross-section”, satisfying a given lower Higgs $p_T$ cut:

$$ \hat{\sigma} \equiv \sigma(p_T(h) > p_T^{cut}) = \int_{p_T(h) \geq p_T^{cut}} dp_T \frac{d\sigma}{dp_T}, \quad (35) $$

and found that, in a NP scenario where $y_q \sim y_q^{SM}$ for all $q = u, d, c, s$ (which corresponds to the UEHiggsY framework discussed here), the above signal strength is significantly smaller than its SM value at the large $p_T(h)$ regime:

$$ R_{hj\rightarrow ffj} \sim 0.3 - 0.4, \quad (36) $$

for $f = b$, $\tau$, $\gamma$, $W$, $Z$ and with a $p_T(h)$ cut in the range $p_T^{cut} \sim 200 - 1000$ GeV.

C. Higgs-photon associated production $pp \rightarrow h\gamma$

In the SM, the leading contribution to the exclusive $pp \rightarrow h\gamma$ production channel is the tree-level $t$-channel hard processes $cc, bb \rightarrow h\gamma$ (shown by the diagram for $qq \rightarrow h\gamma$ in Fig. 2 with $q = c, b$), which give a rather small cross-section of $\sigma(pp \rightarrow h\gamma) \sim \mathcal{O}(0.1) \text{[fb]}$ with a 30 GeV $p_T(h)$-cut at the 13 TeV LHC [35, 40]. The 1-loop SM (EW) diagrams contributing to the light-quark annihilation channels, e.g., $u\bar{u}, d\bar{d} \rightarrow h\gamma$, are more than an order of magnitude smaller than the tree-level $bb$-fusion production channel [35] and the amplitude for the gluon-fusion production channel $gg \rightarrow h\gamma$ vanishes due to Furry’s theorem.

The SM cross-sections for inclusive $h\gamma$ production channels, such as $pp \rightarrow h\gamma + j$, $h\gamma + V(V = W, Z)$, $h\gamma + t\bar{t}$, $h\gamma + t\bar{t}$ are of $\mathcal{O}(1) \text{[fb]}$ at the 13 TeV, whereas the SM cross-section for the inclusive VBF $h\gamma$ production channel $pp \rightarrow h\gamma + 2j$ can reach $\sim 20 \text{[fb]}$ [40, 46].

In our UEHiggsY framework, the exclusive channel $pp \rightarrow h\gamma$ has an appreciably larger rate due to the tree-level ($t$-channel) light-quark fusion diagrams $qq \rightarrow h\gamma$ shown in Fig. 2 (i.e., with $q = u, d, s, c$), which are enhanced by the $O(y_q^{SM})$ $qgh$ Yukawa couplings. In particular, setting again $f_{ij}^t = \delta_{ij}$ and $\Lambda = 1.5 \text{TeV}$ (leading to $y_q \sim y_q^{SM}$), we get $\sigma(pp \rightarrow h\gamma) \sim 1250 \text{[fb]}$, at the 13 TeV LHC and with $p_T(h) > 30$ GeV. Thus, for the exclusive $pp \rightarrow h\gamma$ production channel we find:

$$ R_{h\gamma} \equiv \frac{\sigma(pp \rightarrow h\gamma)}{\sigma(pp \rightarrow h\gamma)_{SM}} \sim 1000, \quad (37) $$

where about 80% of the enhancement arises from the tree-level $u\bar{u}$-fusion diagrams.

Here also, taking into account the subsequent Higgs decay, e.g., $h \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$, we have $R_{h\gamma\rightarrow bb\gamma} = R_{h\gamma\rightarrow \tau^+\tau^-\gamma} = R_{h\gamma\rightarrow \gamma\gamma\gamma} \sim 1000 \times 0.3 \sim 300$, since the UEHiggsY paradigm only effects the Higgs Yukawa couplings to the light quarks.

We note that the exclusive $pp \rightarrow h\gamma$ channel is potentially sensitive to other variants of underlying NP which can be parameterized by different forms of higher dimensional effective operators, i.e., other than the ones associated with the UEHiggsY paradigm in Eq. 1 [48]. In particular, [48] finds that $\sigma(pp \rightarrow h\gamma) \sim \mathcal{O}(10) \text{[fb]}$ can be realized by other types of NP with a typical scale of $\Lambda \sim 1 \text{TeV}$ and Wilson coefficients of $\mathcal{O}(1)$. This is more than an order of magnitude smaller than the effect expected in the UEHiggsY case.

Clearly, differential distributions (e.g., such as the photon transverse momentum distribution [48]) may provide extra handles for disentangling the various types of NP that can effect the $h\gamma$ production channel at the LHC. This is, however, beyond the scope of this work.

D. Higgs-single top associated production $pp \rightarrow th$

The main SM production channels of a Higgs boson in association with a single top quark at hadron colliders are inclusive and have, at LO, two distinguishable underlying hard processes, which include an extra
Another sub-leading single top production channel in the SM is the associated production channel $pp \to th$ at the 13 TeV LHC with a data sample of 35.9 fb$^{-1}$ [50]. No significant deviation from the predicted background was observed and bounds on the FC couplings $\xi_{tu}$ and/or $\xi_{tc}$ were obtained. In particular, the bounds were reported on the branching ratios of the corresponding FC decay channels $t \to uh, ch$, which, when translated to the FC couplings (see derivation below), give $\xi_{tu}, \xi_{tc} \lesssim 0.09$. This bound is more than 4 times larger than the expected strength of these FC couplings in the UEHiggsY framework with which the above values for $R_{th/thj}$ and $R_{th/ihj}$ were obtained (recall that, within the UEHiggs paradigm, we expect $\xi_{tu}, \xi_{tc} \sim y_b^{SM} \sim 0.02$). In other words, the currently reported sensitivity to the exclusive $th$ final state is $\sigma(pp \to th + j) / \sigma(pp \to th + j)_{UEHiggsY} \lesssim 16 \times \sigma(pp \to th + j)_{UEHiggsY}$, since the corresponding UEHiggsY predicted cross-section scales as $\xi_{tu,tc}^2$.

Finally, we note that the currently best direct bounds on $\xi_{tu}$ and $\xi_{tc}$ were obtained by the ATLAS collaboration, which analysed the FC top-quark decays $t \to uh, ch$ in $pp \to tt$ events at a center of mass energy of 13 TeV and with 36.1 fb$^{-1}$ [51]. They found $BR(t \to uh) < 2.4 \cdot 10^{-3}$ and $BR(t \to ch) < 2.2 \cdot 10^{-3}$.

Using Eq. (38) we have (for $m_{u,c}/m_t \to 0$):

$$BR(t \to uh, ch) \approx \frac{m_t}{16\pi \Gamma_t} \cdot \xi_{tu,tc}^2 \sim 0.57 \xi_{tu,tc}^2$$

where $\Gamma_t$ is the total width of the top-quark.

Thus, the above cited ATLAS bounds translate into the bounds $\xi_{tu}, \xi_{tc} \lesssim 0.06$, allowing FC $th$ and $tch$ couplings about 3 times larger than the b-quark Yukawa coupling, i.e., $\xi_{tu}, \xi_{tc} \lesssim 3y_b^{SM}$, which do not rule out the UEHiggsY paradigm with the values $\xi_{tu}, \xi_{tc} \sim y_b^{SM}$.

In Table II we summarize our predictions for the Higgs signals considered in this chapter in the UEHiggsY framework, as well as the corresponding SM predictions and the current limits and sensitivities to some of these signals from the LHC RUN2.

VI. SUMMARY

We have proposed a new framework where the Yukawa couplings of the light quarks of the 1st and 2nd generations, $q = u, d, c, s$, can be as large as the b-quark Yukawa, thus decoupling them from the SM Higgs mechanism, within which a Yukawa coupling of a fermion is proportional to its mass. We have shown that this scenario (which we named the “UEHiggsY paradigm”) is natural, if the typical scale of the NP which is responsible for the enhancement of the light quarks Yukawa couplings is around 1-2 TeV and the heavy (and decoupled) degrees of freedom in the underlying theory have natural couplings of $O(1)$ with the SM quarks. We have studied the UEHiggs-Y paradigm in an EFT setup, where dimension six effective operators yield a Yukawa term $y_q \sim O\left(\frac{f^2}{\Lambda^2}\right)$,
where $\Lambda$ is the typical NP scale and $f$ is a dimensionless coefficient (i.e., the Wilson coefficient in the EFT expansion), which depends on the properties and details of the underlying NP dynamics. In particular, with $\Lambda \sim \mathcal{O}(1)$ TeV and natural Wilson coefficients $f \sim \mathcal{O}(1)$, one obtains $y_q \sim \mathcal{O}(\text{few} \ 10^{-2}) \sim \mathcal{O}(y^\text{SM}_q)$.

We also explore the UEHiggsY scenario in extensions of the SM which contain TeV-scale vector-like quarks (VLQ) with a typical mass of 1-2 TeV, which we matched to the higher dimensional EFT operators. We then discuss the flavor structure of the UEHiggsY Yukawa textures and, in particular, of the VLQ extension, and the sensitivity of the measured 125 GeV Higgs signals to this paradigm.

Finally, we suggest some “smoking gun” signals of the UEHiggsY paradigm that should be accessible to the future LHC runs: multi-Higgs production $pp \to hh, hh\gamma$ and single Higgs production in association with a high $p_T$ jet or photon $pp \to h_j, h\gamma$ and with a single top-quark $pp \to ht$.

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| Higgs signal | SM prediction | our UEHiggsY prediction | Current limit/sensitivity |
|--------------|---------------|--------------------------|---------------------------|
| $R_{hV \to hhV}$ | $\frac{\sigma(pp \to hV \to hhV)}{\sigma(pp \to hV \to hhV)_{\text{SM}}}$ | 1 | $\sim 0.33$ | $\sim 0.9 \pm 0.3$ (ATLAS [30]) |
| $V = Z, W$ | | | | $\sim 1.06 \pm 0.3$ (CMS [41]) |
| $R_{hj \to ffj}$ | $\frac{\sigma(pp \to hj \to ffj + j)}{\sigma(pp \to hj \to ffj + j)_{\text{SM}}}$ | 1 | $\sim 0.3 - 0.4$ | None |
| $f = b, \tau, \gamma, Z, W$ | | | | |
| $p_T(h_j) > 200 \text{ GeV}$ | | | | |
| $\sigma(pp \to h\gamma)$ | | $\sim 0.1 \text{ [fb]}$ | $\sim 1.25 \text{ [pb]}$ | None |
| $p_T(\gamma) > 30 \text{ GeV}$ | | | \(\lesssim 1.5\text{ [pb]}\) | CMS [52] |
| $R_{hh} = \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{\text{SM}}}$ | 1 | $\sim 100$ | None |
| $R_{hh \to b\bar{b}\gamma}$ | 1 | $\sim 10$ | \(\lesssim 19\) (CMS [43]) |
| $R_{hh \to b\bar{b}j}$ | 1 | $\sim 10$ | \(\lesssim 29\) (ATLAS [44]) |
| $R_{hhh} = \frac{\sigma(pp \to hh\gamma)}{\sigma(pp \to hh\gamma)_{\text{SM}}}$ | 1 | $\sim 300$ | None |
| $R_{hh\gamma, hh\gamma}$ | 1 | $\sim 10$ | None |

TABLE II: Some “smoking gun” Higgs signals of the UEHiggsY paradigm at the LHC with c.m. energy of 13 TeV. Also listed are the corresponding SM predictions and the current limits and sensitivities (from the LHC RUN2) to some of the signals. The cases where we did not find an experimental bound/measurement are marked by “None”. The - LHC experimental groups are encouraged to perform a dedicated search in these channels, e.g., the exclusive $pp \to h\gamma$, which may also be important for the search of heavy resonances [52].
