IL NUOVO CIMENTO Vol. 37 C, N. 2 Marzo-Aprile 2014
DOI 10.1393/ncc/i2014-11738-x

Colloquia: LC13

Vector-like quarks: t' and partners

L. Panizzi

School of Physics and Astronomy, University of Southampton
Highfield, Southampton SO17 1BJ, UK

ricevuto il 22 Gennaio 2014

Summary. — Vector-like quarks are predicted in various scenarios of new physics, and their peculiar signatures from both pair and single production have been already investigated in detail. However no signals of vector-like quarks have been detected so far, pushing limits on their masses above 600–700 GeV, depending on assumptions on their couplings. Experimental searches consider specific final states to pose bounds on the mass of a vector-like quark, usually assuming it is the only particle that contributes to the signal of new physics in that specific final state. However, realistic scenarios predict the existence of multiple vector-like quarks, possibly with similar masses. The reinterpretation of mass bounds from experimental searches is therefore not always straightforward. In this analysis I briefly summarise the constraints on vector-like quarks and their possible signatures at the LHC, focusing in particular on a model-independent description of single production processes for vector-like quark that mix with all generations and on the development of a framework to study scenarios with multiple vector-like quarks.

PACS `14.65.Jk` – Other quarks (e.g., 4th generations).
PACS `13.85.Rm` – Limits on production of particles.
PACS `12.15.Ff` – Quark and lepton masses and mixing.

1. – Introduction

After the discovery of a new resonance that matches the expectations for a Standard Model Higgs boson, the LHC experiments are now focusing on New Physics Searches. One of the Holy Grails of particle physics is the issue of naturalness, and of course the solution of the mystery of the nature of Dark Matter. The discovery of a Higgs candidate at a mass of 125 GeV, thus very close to the electroweak scale, is in fact a realisation of the naturalness problem: why is the scalar mass so close to the electroweak scale? What symmetry, if any, is shielding it from large loop corrections from heavy physics?

The quest for an answer to such questions has been one of the guiding principles behind the flourishing of model building in the past decades. A general assumption of these models is the presence of new weakly coupled states which effectively cut-off the divergent loop contributions to the Higgs mass from Standard Model states, mainly the top quark and the massive gauge bosons $W^{\pm}$ and Z. The absence of fine-tuning would therefore require the masses of the hypothetical new states to lay below or around the TeV scale. As the top quark is known to have the largest Yukawa coupling to the Higgs field, it is a natural expectation that the lightest new states are partners of the top itself.

From the theoretical side there are several models which address the naturalness issue or postpone it to higher scales. Supersymmetry, the most popular theory of New Physics, predicts the existence of states with different statistics: therefore, the top quark would be complemented by scalar tops. Some models are based on the effective Lagrangian approach, others introduce extended global symmetries (Little Higgs models) [1], extra dimensional space symmetries (Gauge-Higgs Unification) [2-4] or assume that the breaking of the electroweak symmetry is due to a strongly interacting dynamics (Composite Higgs models) [4]. Modern incarnations of Technicolour, which have a light Higgs-like scalar in the spectrum [5, 6], should also be included in the list. In all the above cases, a common prediction is the presence of partners of the top quark and more generally multiplets containing a top partner of the vector-like type [7], which have the same spin and only differ in the embedding into representations of the weak isospin, $SU(2)_L$. They typically arise as Kaluza-Klein recursions of the quarks in models of extra dimensions [8], states needed to complete a full representation of the extended symmetries or additional massive composite states of the strong dynamics [8-10]. Also, the possibility for new heavy quarks featuring s-channel resonances remains of prime interest at the LHC. Contrary to sequential fourth family quarks which are heavily constrained from the Higgs boson searches due to their non-decoupling properties [11], indirect bounds on non-chiral quarks are much weaker: they nevertheless affect the properties of the Higgs [12, 13], for instance affecting the production of a pair of Higgses [14], or offering new Higgs production mechanisms [15-18]. The phenomenology of new heavy quarks has been widely studied in literature, see for example [25, 19-24] and the forthcoming direct searches at the LHC will therefore play a fundamental role in testing the large number of models predicting the existence of these states. The minimal scenarios with the presence of new vector-like quarks (VLQs) besides SM particles are those in which the new states interact with SM quarks and the Higgs boson through Yukawa couplings. Classifying VLQs in multiplets of $SU(2)_L$, it is possible to write gauge-invariant interaction terms only for singlets, doublets and triplet representations. All the possibilities are shown in table I. Pure mixing terms between VLQs and SM states, allowed by gauge invariance for singlets and SM-like doublet representations, have been omitted because they can be eliminated through rotations of the states.

The importance of top partners, or generically new quarks, is also supported by the massive ongoing experimental effort for their discovery: many searches are being done by both CMS and ATLAS. The most recent results do not assume exclusive decays in specific channels, but consider general scenarios, where the new quarks can decay to different final states. The combined results of CMS and ATLAS searches can be found on the respective twiki pages [26]: the current experimental bounds on new heavy quarks are in the range 600–800 GeV depending on the decay channel. Still, experimental searches assume that new quarks only couple to third generation SM quarks; though this is a natural expectation, mixings with lighter generations are not at all forbidden, and they can provide different signatures or affect the number of events in the final states tested by experiments, thus modifying current bounds.

TABLE I. – *Allowed representations for VLQs, with quantum numbers under $SU(2)_L$ and $U(1)_Y$ and Yukawa mixing terms in the Lagrangian. Depending on the chosen representation, the Higgs boson may be H or H^c, therefore it has been noted as $H^{(c)}$ when necessary. The gauge invariant mass term common to all representations is a peculiar feature of VLQs.*

	SM quarks	Singlets		Doublets			Triplets	
	$\begin{pmatrix}u\\d\end{pmatrix}$ $\begin{pmatrix}c\\s\end{pmatrix}$ $\begin{pmatrix}t\\b\end{pmatrix}$	(U)	(D)	$\begin{pmatrix}X\\U\end{pmatrix}$	$\begin{pmatrix}U\\D\end{pmatrix}$	$\begin{pmatrix}D\\Y\end{pmatrix}$	$\begin{pmatrix}X\\U\\D\end{pmatrix}$	$\begin{pmatrix}U\\D\\Y\end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	−1/3	7/6	1/6	−5/6	2/3	−1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	
$\mathcal{L}_m$	not allowed	$-M\bar{\psi}\psi$						

2. – Constraints on model parameters

The presence of new states induces corrections to precisely measured observables of the SM both at tree level and at loop level. Tree level modifications are robust, in the sense that they can affect observables which in the SM are generated only at loop level and because they only depend on mixing parameters and new particles representations. Loop corrections are more model-dependent: however, the presence of new heavy states can result in cancellations between diagrams which can sensibly change loop-level observables. In the following a short review of the main observables which can provide constraints on the mixing parameters of VLQs is provided, considering the most recent experimental measurements; more details on analyses and formulas can be found in [27, 25, 28, 29] for the singlet or SM-doublet scenarios, or in [30] for the non-SM doublet ($X_{5/3}\ t'$) scenario.

Tree-level constraints. – Allowing a mixing between VLQ and SM quarks means that couplings of the type Vq_1q_2, where $V = W, Z$ and $q_{1,2}$ are SM quarks, receive deviations which can be observable in experimental searches. Such deviations depend on the mixing parameters of the new states and on their representations, allowing the possibility to pose strong bounds on the coupling between VLQs and SM particles.

If the VLQs mix only with third generation SM quarks, the only affected observables are Wtb and Zbb; since either the top or bottom quarks are mixed with the new states in all representations, the CC coupling Wtb is always affected at tree level by the presence of VLQ, while the NC coupling Zbb is modified at tree level only if a b' VLQ is present.

If the VLQs mix with lighter generations a number of observables is affected: FCNC can contribute at tree level to SM observables that otherwise would receive only loop-level contributions. The main observables which can be modified at tree-level by the presence of new VLQs are listed in the following (see [24] and [30] for more details):

- Rare FCNC top decays at tree level: possible only if new quarks mix with both light and third generations.
- Zqq couplings: the contributions are at tree level only if there is mixing between the VLQ and the considered quark. The contribution to the coupling is at loop level if there is no mixing (*e.g.* the contribution of a t' singlet to Zbb).
- Meson mixing and decays at tree level: some processes which in the SM can only occur at loop level may be generated at tree-level through FCNCs, provided new quarks mix with light generations.
- Atomic parity violation: a strong bound on mixing parameters between VLQs and the first quark generation comes from measurements of the atomic parity violation, which provides information about Zuu and Zdd couplings.
- Tree level modifications to the CKM matrix: the contribution of VLQs strongly depend on the scenario considered. The very presence of a CKM matrix in the right-handed sector is linked to the existence of both a top and a bottom VL partner

Loop-level constraints. – Loop constraints are more model dependent: deviations from SM predictions may occur only if specific particles circulate in loops, but the particle content of the theory depends on which representation the VLQs belong to, and in many cases, SM quantities are not affected at all. The main observables which can be affected by VLQs at loop level are listed in the following (see [24] and [30] for more details):

- EW precision tests: regardless of the representation the VLQ belongs to, the new states induce modification at loop level to the vacuum polarizations of electroweak gauge bosons, which are parametrised by the oblique parameters S, T, U [31].
- Rare FCNC top decays at loop level: VLQs may contribute at loop level to FCNC top decays which are GIM suppressed in the SM. The presence of modified couplings can be competitive with the SM diagram.
- Meson mixing and decays at loop level: new quarks can circulate in loops together with SM particles, and even small corrections can spoil cancellations within loop diagrams, producing observable effects. Such phenomena can be particularly relevant for meson mixing, especially if VLQs belong to a representation for which tree level diagrams are not allowed.

3. – Signatures at the LHC

The identification of the channels which may lead to the discovery of VLQs at the LHC depends on the scenario under consideration. In general, processes dominated by QCD, such as pair production, have the advantage of being more model independent, as the production cross-section only depends on the VLQ mass, while single production is driven by more model-dependent processes, even if it is possible to parametrise both production and decays in terms of few parameters [32]. However, pair production suffers from a suppression due to PDF rescaling with respect to single production, and if the VLQ mass is large enough, single production dominates over pair production. The VLQ mass corresponding to the equivalence between pair and single production cross sections depends on the specific model. Excluding purely QCD processes, the production of VLQs

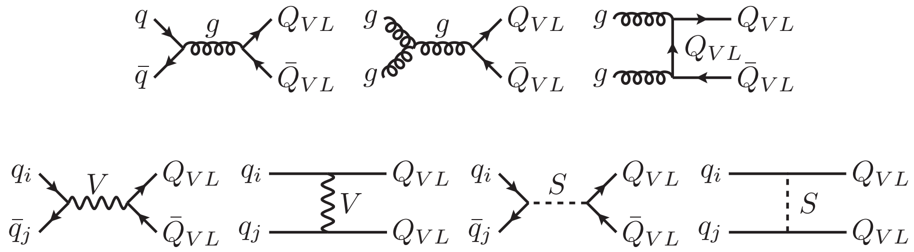

Fig. 1. – Feynman diagrams for pair production of a generic VLQ. Above the dominant and model-independent QCD contributions, below the subdominant and model-dependent EW contributions. Arrows on fermion lines have been removed to account for both particles and antiparticles, when necessary. Notice the possibility to have FCNCs between SM quarks in the V and S s-channel diagram, which is peculiar to VL scenarios.

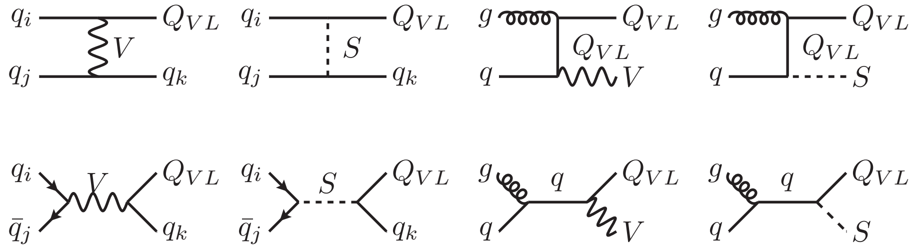

Fig. 2. – Feynman diagrams for single production of a generic VLQ. VLQs can interact with SM quarks both through charged currents and neutral currents, allowing FCNCs also within SM states in diagrams with q_i-q_j-$\{V, S\}$ interactions. Arrows on fermion lines have been removed to account for both particles and antiparticles, when necessary. Notice that not all diagrams are allowed for a specific VL quark (*e.g.*, neutral currents are not allowed for quarks with exotic electric charges).

is related to the interaction of the new states with SM particles. If VLQs interact with SM quarks through Yukawa couplings, a mixing is induced between quarks of different families, giving rise to FCNCs. On the other hand, in scenarios such as minimal universal extra-dimensions, the KK-odd VLQs do not mix with SM quarks and therefore they can only be produced in pairs or together with another KK-odd state.

The Feynman diagrams for pair and single production of VLQs are shown in figs. 1, 2.

3·1. *Model-independent parametrisation of single production.* – More details about the parametrisation can be found in [32]. For concreteness, we first focus on the case of a top partner T, *i.e.* a VL quark with the same electric charge (and colour) as the top quark. The most general couplings of a single T with the electroweak gauge bosons can be parametrised as

$$\begin{aligned}(1)\qquad \mathcal{L}_{T single} = {} & \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}}\, [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}] + \kappa_Z V^{4i}_{L/R} \frac{g}{2c_W}\, [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] \\ & - \kappa_H V^{4i}_{L/R} \frac{M}{v}\, [\bar{T}_{R/L} H u^i_{L/R}] + \text{h.c.}\end{aligned}$$

while the couplings with gluon and photon are standard and dictated by gauge invariance (^{1}). This is a generalisation of the Lagrangian in [33] by the inclusion of couplings with the Higgs [34], and to all the generations of quarks at the same time. In this formula, M is the mass of the VL quark, $V^{4i}_{L/R}$ represent the mixing matrices between the new quarks and the three Standard Model generations labelled by i, while the parameters κ_V ($V = W,\ Z,\ H$) encode the coupling to the three bosons. The normalisation is chosen so that for $\kappa_W = \kappa_Z = \kappa_H = 1$, the VL top decays 25% to Z and H and 50% to W in the asymptotic limit where the mass M goes to infinity, in agreement with what is expected from the Goldstone equivalence theorem. The values of the κ_V's are determined by the $SU(2)_L$ representation T belongs to, and eventually by mixing to other VL representations.

In the most general set-up, T may have sizeable couplings to both left- and right-handed Standard Model quarks q. However, in the case of one single light VL quark, which is the simple case studied experimentally, it is easy to show that only one of the two mixing angles is large, the other being suppressed by a factor of m_q/M [35]. Following this observation, we can simplify the parametrisation by neglecting the suppressed mixing angles, so that the Lagrangian we showed above will only contain one of the two chiral couplings: this approximation may not be precise for the top quark, while it is numerically well justified for all other quarks.

From the Lagrangian in eq. (1), the partial widths in the various channels are given by

$$\Gamma(T \to W d_i) = \kappa_W^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \Gamma_W(M, m_W, m_{d_i})\,, \tag{2}$$

$$\Gamma(T \to Z u_i) = \kappa_Z^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \Gamma_Z(M, m_Z, m_{u_i})\,, \tag{3}$$

$$\Gamma(T \to H u_i) = \kappa_H^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \Gamma_H(M, m_H, m_{u_i})\,, \tag{4}$$

where the kinematic functions are

$$\Gamma_W = \lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_W^2}{M^2}) \left[\left(1 - \frac{m_q^2}{M^2}\right)^2 + \frac{m_W^2}{M^2} - 2\frac{m_W^4}{M^4} + \frac{m_W^2 m_q^2}{M^4} \right]\,, \tag{5}$$

$$\Gamma_Z = \frac{1}{2}\lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_Z^2}{M^2}) \left[\left(1 - \frac{m_q^2}{M^2}\right)^2 + \frac{m_Z^2}{M^2} - 2\frac{m_Z^4}{M^4} + \frac{m_Z^2 m_q^2}{M^4} \right]\,, \tag{6}$$

$$\Gamma_H = \frac{1}{2}\lambda^{\frac{1}{2}}(1, \frac{m_q^2}{M^2}, \frac{m_H^2}{M^2}) \left[1 + \frac{m_q^2}{M^2} - \frac{m_H^2}{M^2} \right]\,; \tag{7}$$

and the function $\lambda(a, b, c)$ is given by

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc\,. \tag{8}$$

(^{1}) Couplings to the Z, and to the W and other VL quarks, are also in general present and they depend on the representation of $SU(2)_L$ T belongs to.

We expressed the partial width in a fashion that underlines the universal coupling factor, so that the difference between various channels only depends on the masses: for the light quarks, the mass dependence is very mild, therefore we can assume that the numbers are the same for all generations. This is not true in general for the top quark, for which the effect of its mass may be important: as we neglected it in the mixing angles, we will consistently neglect it here.

Neglecting all quark masses, therefore, the branching ratios can be written as

$$BR(T \to V q_i) = \frac{\kappa_V^2 |V^{4i}_{L/R}|^2 \Gamma^0_V}{\left(\sum_{j=1}^3 |V^{4j}_{L/R}|^2\right)\left(\sum_{V'=W,Z,H} \kappa^2_{V'} \Gamma^0_{V'}\right)}\,, \tag{9}$$

where Γ^0_V are the kinematic functions for zero quark mass $m_q = 0$:

$$\Gamma^0_W = \left(1 - 3\frac{m_W^4}{M^4} + 2\frac{m_W^6}{M^6}\right) \sim 1 + \mathcal{O}(M^{-4})\,, \tag{10}$$

$$\Gamma^0_Z = \frac{1}{2}\left(1 - 3\frac{m_Z^4}{M^4} + 2\frac{m_Z^6}{M^6}\right) \sim \frac{1}{2} + \mathcal{O}(M^{-4})\,, \tag{11}$$

$$\Gamma^0_H = \frac{1}{2}\left(1 - \frac{m_H^2}{M^2}\right)^2 \sim \frac{1}{2} - \frac{m_H^2}{M^2} + \mathcal{O}(M^{-4})\,. \tag{12}$$

These branching ratios can be defined in terms of four independent parameters which contain all the available information:

$$\zeta_i = \frac{|V^{4i}_{L/R}|^2}{\sum_{j=1}^3 |V^{4j}_{L/R}|^2}\,, \qquad \sum_{i=1}^3 \zeta_i = 1\,, \tag{13}$$

$$\xi_V = \frac{\kappa_V^2 \Gamma^0_V}{\sum_{V'=W,Z,H} \kappa^2_{V'} \Gamma^0_{V'}}\,, \qquad \sum_{V=W,Z,H} \xi_V = 1\,; \tag{14}$$

so that

$$BR(T \to V q_i) = \zeta_i \xi_V\,. \tag{15}$$

For experimental purposes, the decays into first or second generation cannot be distinguished: one can therefore express all the results in terms of the decay rates into light generations via $\zeta_{jet} = \zeta_1 + \zeta_2 = 1 - \zeta_3$:

$$BR(T \to Zj) = \zeta_{jet}\xi_Z\,,\ \ BR(T \to Zt) = (1 - \zeta_{jet})\xi_Z\,, \tag{16}$$

$$BR(T \to Hj) = \zeta_{jet}(1 - \xi_Z - \xi_W)\,,\ \ BR(T \to Ht) = (1 - \zeta_{jet})(1 - \xi_Z - \xi_W)\,, \tag{17}$$

$$BR(T \to W^+ j) = \zeta_{jet}\xi_W\,,\ \ BR(T \to W^+ b) = (1 - \zeta_{jet})\xi_W\,. \tag{18}$$

When studying pair production of T, which is dominated by model-independent QCD processes only sensitive to the mass of the VL quark, the phenomenology of the T can be therefore completely described in terms of 4 independent parameters: the mass M, ξ_W, ξ_Z and ζ_{jet}. As will be clear later, single production processes may be sensitive to the separate values of ζ_1 and ζ_2, so the number of relevant parameters can be increased by one unit.

We can finally re-express the Lagrangian in eq. (1) in terms of the relevant 5 parameters as follows:

$$\begin{aligned}\mathcal{L} = \kappa_T \Bigg\{ &\sqrt{\frac{\zeta_i \xi_W}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d^i_{L/R}] + \sqrt{\frac{\zeta_i \xi_Z}{\Gamma_Z^0}} \frac{g}{2c_W} \, [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] \\ &- \sqrt{\frac{\zeta_i (1-\xi_Z-\xi_W)}{\Gamma_H^0}} \frac{M}{v} \, [\bar{T}_{R/L} H \; u^i_{L/R}] \Bigg\} + \text{h.c.} \quad \text{with} \quad \zeta_3 = 1-\zeta_1-\zeta_2 \,. \end{aligned} \tag{19}$$

The new parameter κ_T is an overall coupling strength measure: it is not relevant for the branching ratios, nor for pair production (which is to a very good approximation due to QCD processes), however it will determine the strength of single production. It can be written in terms of the parameters in the starting Lagrangian as

$$\kappa_T = \sqrt{\sum_{i=1}^{3} |V^{4i}_{L/R}|^2} \sqrt{\sum_V \kappa_V^2 \Gamma_V^0} \,. \tag{20}$$

It is important to notice that the $V^{4i}_{L/R}$ matrix elements are, in general, complex quantities as phases may be present in the mixing with light quarks. Since the parameters ζ_i are proportional to the square of mixing matrix entries, the information about phases is lost in the parametrisation in eq. (19). Such phases are crucial when considering, for instance, flavour bounds on couplings, however they will play a minor role in the LHC phenomenology which is the main focus of this parametrisation. Phases are potentially relevant only in single production processes where interference terms give a sizeable contribution, which is not the case in the production modes we will consider in this work, as it will be clear in the following sections.

So far, we have completely and consistently neglected the contribution of the top mass both in the kinematic functions and in the suppressed couplings. However, for VL quark masses below a TeV, the effects may be numerically relevant. The effect of the suppressed coupling, which is often dominant, introduces model dependence, therefore we would be forced to introduce new parameters in our Lagrangian. On the other hand, in simple models such effects are always small, being below 10–20% for $M = 600\,\text{GeV}$ (which is the level of present exclusion from direct searches at the LHC), therefore we will neglect their effect for now. The only exception is the channel $T \to Ht$: in this case, however, the sub-leading term is independent on the representation T belongs to. The latter coupling originates from the mass mixing between the VL quark and the SM top. Allowing for this mixing automatically generates such a coupling. It also turn out that the effect of the phase space is sub-dominant, and the main contribution comes from the new coupling. For this reason, we suggest to complement the Lagrangian in eq. (19) with an additional term:

$$\Delta\mathcal{L}_{T\ single} = -\kappa_T \sqrt{\frac{\zeta_3 (1-\xi_Z-\xi_W)}{\Gamma_H^0}} \frac{m_t}{v} \, [\bar{T}_{L/R} H \; u^i_{R/L}] + \text{h.c.} \,, \tag{21}$$

where the new term has opposite chiralities compared to the one in eq. (19), and is suppressed by a factor m_t/M. No extra free parameter needs to be introduced. The addition of this term modifies the relation between the parameters ζ_i and ξ_V with the branching ratios of the T:

$$BR(T \to Ht) = \frac{\zeta_3 \xi_H (1+\delta_H)}{1+\zeta_3\xi_H\delta_H}\,, \tag{22}$$

while for all other channels

$$BR(T \to V q_i) = \frac{\zeta_i \xi_V}{1+\zeta_3\xi_H\delta_H}\,. \tag{23}$$

The correction δ_H is a simple function of the mass of the VL quark, and it is given by

$$\delta_H = \frac{\lambda^{1/2}(1, \frac{m_H^2}{M^2}, \frac{m_t^2}{M^2})}{\left(1-\frac{m_H^2}{M^2}\right)^2}\left[\left(1+\frac{m_t^2}{M^2}-\frac{m_H^2}{M^2}\right)\left(1+\frac{m_t^2}{M^2}\right)+4\frac{m_t^2}{M^2}\right]-1 \sim 5\frac{m_t^2}{M^2}\,, \tag{24}$$

where we expanded the result at leading order in $1/M^2$. Numerically, this effect is $\delta_H \sim 39\%$ for $M = 600\,\text{GeV}$, and it therefore leads to a substantial enhancement of the decay rate in Ht.

The discussion for the T top partner, can be generalised to the other 3 kinds of VL quarks. Therefore, the most complete effective model apt to describe their phenomenology would contain the following 4 sets of interactions:

$$\begin{aligned}
\mathcal{L} = \kappa_T &\left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}}\frac{g}{\sqrt{2}}\,[\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}}\frac{g}{2c_W}\,[\bar{T}_L Z_\mu \gamma^\mu u_L^i] \right. \\
&\left. - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}}\frac{M}{v}\,[\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}}\frac{m_t}{v}\,[\bar{T}_L H t_R] \right\} \\
&+\kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}}\frac{g}{\sqrt{2}}\,[\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}}\frac{g}{2c_W}\,[\bar{B}_L Z_\mu \gamma^\mu d_L^i] \right. \\
&\left. - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}}\frac{M}{v}\,[\bar{B}_R H d_L^i] \right\} \\
&+\kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}}\frac{g}{\sqrt{2}}\,[\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}}\frac{g}{\sqrt{2}}\,[\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + \text{h.c.}\,,
\end{aligned} \tag{25}$$

for leading left-handed mixing, while it suffices to exchange the chiralities L ↔ R for leading right-handed coupling. Note that ξ_V^T and ξ_V^B are in general different, also in models where the two VL quarks belong to the same representation. In principle, the rates in the 3 generations may also be different, however this is not the case in the simplest cases. In typical models only one of the two mixings is large, and the other suppressed. This effective Lagrangian has been implemented in FeynRules [36, 37].

3˙2. *General scenarios with multiple vector-like quarks.* – Usually experimental searches for vector-like quarks adopt a phenomenological approach, assuming that only one new Q_V state is present beyond the SM. Most models, however, predict in general the existence of a new *quark sector*, which implies the presence of more than one new coloured state, possibly degenerate or nearly degenerate. It is possible to analyse the phenomenology of scenarios with multiple vector-like quarks by decomposing the signal in simplified topologies. The possible decay chains of a t' that interacts with the SM through Yukawa interactions are only 9, and they correspond to all the channels built with combinations of the SM bosons W, Z, H and the SM quarks. Experimentally, however, light quarks are indistinguishable, and therefore the number of possible decay channels reduces to 6 (assuming to be able to distinguish the bottom quark through b-tagging). Considering also the remaining three VLQ species, and assuming the model-independent QCD pair production, the number of possible states containing SM particles that can be produced after the decay of the VLQs are 80. Performing a MC simulation for each of the 80 channels and for different masses of the VLQs allows to reconstruct the signal for any number of VLQs with any combination of BRs. Computing the experimental efficiencies for given searches allows then to determine the exclusion confidence levels for any given benchmark (*i.e.* spectrum and BRs of the new quarks). This project is under development, and more details and results will be provided in a dedicated forthcoming publication.

4. – Conclusions

A minimal extension of the SM with the presence of vector-like quarks has a huge and interesting range of possible signatures, some of which have already been tested at the LHC. Current bounds on the mass of vector-like quarks are around 600–800 GeV, depending on assumptions on their mixing and decay channels and a huge experimental effort is ongoing for testing new channels and single production processes. However, experimental searches still rely on mixing with third generation only, while if vector-like quarks mix with all SM families many searches must be reinterpreted, and dedicated, optimized, searches may be in order. Furthermore new tools are under development to allow a reinterpretation of experimental data for testing scenarios with multiple new quarks. The discovery of a new fermionic coloured state would certainly be a major and exciting event at the LHC, thus a detailed understanding of its properties will be extremely useful for future analyses.

REFERENCES

[1] Arkani-Hamed N., Cohen A. G., Katz E. and Nelson A. E., *JHEP*, **0207** (2002) 034 [arXiv:hep-ph/0206021]; Schmaltz M. and Tucker-Smith D., *Ann. Rev. Nucl. Part. Sci.*, **55** (2005) 229 [arXiv:hep-ph/0502182].

[2] Antoniadis I., Benakli K. and Quiros M., *New J. Phys.*, **3** (2001) 20 [hep-th/0108005].

[3] Hosotani Y., Noda S. and Takenaga K., *Phys. Lett. B*, **607** (2005) 276 [hep-ph/0410193].

[4] Agashe K., Contino R. and Pomarol A., *Nucl. Phys. B*, **719** (2005) 165 [hep-ph/0412089].

[5] Matsuzaki S. and Yamawaki K., *Phys. Lett. B*, **719** (2013) 378 [arXiv:1207.5911 [hep-ph]].

[6] Foadi R., Frandsen M. T. and Sannino F., *Phys. Rev. D*, **87** (2013) 095001 [arXiv:1211.1083 [hep-ph]].

[7] del Aguila F. and Bowick M. J., *Nucl. Phys. B*, **224** (1983) 107 [preprint UFTP-82-19].

[8] Contino R., Da Rold L. and Pomarol A., *Phys. Rev. D*, **75** (2007) 055014 [arXiv:hep-ph/0612048].

[9] Matsedonskyi O., Panico G. and Wulzer A., *JHEP*, **1301** (2013) 164 [arXiv:1204.6333 [hep-ph]].

[10] Dissertori G., Furlan E., Elisabetta, Moortgat F. and Nef P., *JHEP*, **1009** (2010) 019 [arXiv:1005.4414 [hep-ph]].

[11] Eberhardt O., Herbert G., Lacker H., Lenz A., Menzel A., Nierste U. and Wiebusch M., *Phys. Rev. Lett.*, **109** (2012) 241802 [arXiv:1209.1101 [hep-ph]].

[12] Moreau G., *Phys. Rev. D*, **87** (2013) 015027 [arXiv:1210.3977 [hep-ph]].

[13] Bonne N. and Moreau G., *Phys. Lett. B*, **717** (2012) 409 [arXiv:1206.3360 [hep-ph]].

[14] Contino R., Ghezzi M., Moretti M., Panico G., Piccinini F. and Wulzer A., *JHEP*, **1208** (2012) 154 [arXiv:1205.5444 [hep-ph]].

[15] Aguilar-Saavedra J. A., *JHEP*, **0612** (2006) 033 [hep-ph/0603200].

[16] Azatov A., Bondu O., Falkowski A., Felcini M., Gascon-Shotkin S., Ghosh D. K., Moreau G. and Sekmen S., *Phys. Rev. D*, **85** (2012) 115022 [arXiv:1204.0455 [hep-ph]].

[17] Harigaya K., Matsumoto S., Nojiri M. M. and Tobioka K., *Phys. Rev. D*, **86** (2012) 015005 [arXiv:1204.2317 [hep-ph]].

[18] Carmona A., Chala M. and Santiago J., *JHEP*, **1207** (2012) 049 [arXiv:1205.2378 [hep-ph]].

[19] del Aguila F., Perez-Victoria M. and Santiago J., *JHEP*, **0009** (2000) 011 [hep-ph/0007316].

[20] Aguilar-Saavedra J. A., *Phys. Lett. B*, **625** (2005) 234 [Erratum-ibid. B **633** (2006) 792] [hep-ph/0506187].

[21] Cynolter G. and Lendvai E., *Eur. Phys. J. C*, **58** (2008) 463 [arXiv:0804.4080 [hep-ph]].

[22] Aguilar-Saavedra J. A., *JHEP*, **0911** (2009) 030 [arXiv:0907.3155 [hep-ph]].

[23] Berger J., Hubisz J. and Perelstein M., *JHEP*, **1207** (2012) 016 [arXiv:1205.0013 [hep-ph]].

[24] Okada Y. and Panizzi L., *Adv. High Energy Phys.*, **2013** 364936 [arXiv:1207.5607 [hep-ph]].

[25] Lavoura L. and Silva J. P., "The Oblique corrections from vector - like singlet and doublet quarks," *Phys. Rev. D*, **47** (1993) 2046.

[26] ATLAS twiki:
`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults`,
CMS twiki: `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G`.

[27] Branco G. C. and Lavoura L., "On The Addition Of Vector Like Quarks To The Standard Model," *Nucl. Phys. B*, **278** (1986) 738.

[28] Aguilar-Saavedra J. A., "Effects of mixing with quark singlets," *Phys. Rev. D*, **67** (2003) 035003 [Erratum-ibid. D **69** (2004) 099901] [hep-ph/0210112].

[29] Arnold J. M., Fornal B. and Trott M., *JHEP*, **1008** (2010) 059 [arXiv:1005.2185 [hep-ph]].

[30] Cacciapaglia G., Deandrea A., Panizzi L., Gaur N., Harada D. and Okada Y., "Heavy Vector-like Top Partners at the LHC and flavour constraints," *JHEP*, **1203** (2012) 070 [arXiv:1108.6329 [hep-ph]].

[31] Peskin M. E. and Takeuchi T., "Estimation of oblique electroweak corrections," *Phys. Rev. D*, **46** (1992) 381.

[32] Buchkremer M., Cacciapaglia G., Deandrea A. and Panizzi L., *Nucl. Phys. B*, **876** (2013) 376 [arXiv:1305.4172 [hep-ph]].

[33] Atre A., Azuelos G., Carena M., Han T., Ozcan E., Santiago J. and Unel G., *JHEP*, **1108** (2011) 080 [arXiv:1102.1987 [hep-ph]].

[34] Atre A., Chala M. and Santiago J., *JHEP*, **1305** (2013) 099 [arXiv:1302.0270 [hep-ph]].

[35] Cacciapaglia G., Deandrea A., Harada D. and Okada Y., *JHEP*, **1011** (2010) 159 [arXiv:1007.2933 [hep-ph]].

[36] Christensen N. D. and Duhr C., *Comput. Phys. Commun.*, **180** (2009) 1614 [arXiv:0806.4194 [hep-ph]].

[37] `http://feynrules.irmp.ucl.ac.be/wiki/VLQ`.