MODEL-INDEPENDENT ANALYSIS OF SCENARIOS WITH VECTOR-LIKE QUARKS*

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The phenomenology at the LHC of scenarios containing new heavy vector-like quarks is discussed. Focus will be given to their main production and decay channels, and a new method to analyse scenarios of new physics with the presence of multiple vector-like quarks with generic hypotheses about their couplings to SM quarks will be introduced.

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1. Introduction

The discovery at the LHC of a new scalar boson with properties remarkably similar to those expected for the Higgs boson has been a crucial landmark for the completion of the Standard Model. However, the very presence of the Higgs boson leaves open many issues, both experimental and theoretical. On the observational side, the SM cannot explain the existence of Dark Matter, the measured baryon asymmetry of the Universe, and the pattern in neutrino oscillations; on the theoretical side, the solution to the naturalness problem, the origin of families or the gauge coupling non-unification at high energies remain mysteries that strongly point towards the existence of new physics that may be accessible at current LHC energies. Indeed, the newly discovered scalar particle has a mass which is very close to the electroweak symmetry breaking scale and it is, therefore, natural to wonder if there is any new symmetry protecting it to achieve large loop corrections. Trying to find solutions to such problems has resulted in the development of a plethora of models of new physics beyond the Standard Model, which predict the existence of various new particles with signatures that can be observed at the LHC. A generic assumption of these models

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is the existence of new states that can compensate the divergences in the Higgs loops. These divergences are mainly due to the heaviest particles of the SM circulating in the loops, and, therefore, it is natural to infer that models of new physics will contain partners of the top quark. Supersymmetry predicts the existence of scalar partners of the top, while models based on extended global symmetries, like the Little Higgs [1–6], symmetries in the extra-dimensional space, like the gauge-Higgs unification [7–9], or models where a strong dynamics is responsible for electroweak symmetry breaking, like the composite Higgs [10–19], generally predict the existence of fermionic top partners with vector-like properties[1] and belonging, in general, to different representations of the EW gauge group. New vector-like quarks (VLQs) appear also as Kaluza–Klein excitations in extra-dimensional scenarios, corresponding to heavy partners of SM states. Experimental bounds on VLQs are weaker than the corresponding limit on a chiral fourth family extension of the SM, which has non-decoupling properties. On the other hand, VLQs can affect the Higgs production rates because of their potential decays into Higgs bosons and SM quarks. The phenomenology of VLQs has been widely studied in literature [20–33] and many experimental searches have been devoted to the detection of VLQs decaying into specific channels [34], though no signal has been found so far. The focus of this contribution is to describe a model-independent procedure to analyse scenarios with the presence of multiple VLQs with general hypotheses about their decay to SM states and to provide conservative exclusion limits.

2. Embedding VLQs in the SM

Considering the minimal extension of the SM containing one vector-like quark, and assuming that it can interact with SM states only through Yukawa couplings, it is possible to classify all the possible SU(2) representations for which gauge-invariant interaction terms with SM states are allowed. The only allowed possibilities are singlets, doublets and triplets, and a summary of their quantum numbers and Lagrangian terms is provided in Table I.

After the Higgs gets a VEV, a mixing between VLQs and SM quarks is allowed. It occurs in the left-handed sector for singlets and triplets and in the right-handed sector for doublets, and the resulting mass eigenstates can be partners of the top or bottom quarks (labelled as T and B respectively) or exotic states with charges $5/3$ or $-4/3$ (labelled as X and Y respectively).

[1] A fermion is defined to be vector-like under a given gauge group if its left- and right-handed components belong to the same representation of the gauge group. In this context, quarks are defined to be vector-like with respect to the gauge group of the EW sector of the SM, $SU(2) \times U(1)$.

TABLE I

Allowed representations for VLQs, with quantum numbers under $SU(2)_L$ and $U(1)_Y$ and Yukawa mixing terms in the Lagrangian. In the first column, the same properties are summarized for SM chiral quarks, to allow comparison. 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	$-M\bar{\psi}\psi$		

The top and bottom partners can couple to SM quarks through both charged and neutral currents involving the SM gauge bosons W and Z or the Higgs boson. The exotic states X and Y can only couple to SM quarks through charged currents. If more than one VLQ representation is added to the SM, Yukawa couplings between VLQs may occur, and states with more exotic charges $(8/3, -7/3, 11/3, -10/3, \ldots)$ may appear. However, only the four VLQs appearing in the minimal extension of the SM (T, B, X and Y) can decay directly into SM states, and for this reason they are crucial in the determination of a model-independent framework for the analysis of more complex scenarios. Indeed, the presence of VLQ with charges higher than $5/3$ or lower than $-4/3$ requires the presence of the minimal exotic VLQs to allow decays into SM quarks, via chain decays into resonant or excited states of the $5/3$ or $-4/3$ quarks. Of course, the presence of new states induces corrections to precisely measured observables of the SM. These corrections can be at either tree or loop level. Tree-level corrections only depend on mixing parameters and on particle representations and may affect observables that are generated at loop level in the SM. Modifications at loop level are more model dependent, as relevant cancellations between diagrams are related to specific particles circulating in the loop, and because in the same loops other new particles, as heavy gauge bosons or new scalars, can circulate. More details on all the observables that can constrain the mixing parameters of VLQs can be found in [20, 21, 23, 28, 30, 31].

3. Signatures of VLQs at the LHC

Identifying the best channels which may lead to an observation of VLQs at the LHC requires a model-dependent analysis. However, 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. Single production, on the other hand, is driven by more model-dependent processes, even if it is possible to parametrise both production and decays in terms of few parameters [32]. 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 value which corresponds to the equivalence between pair and single production cross sections depends on the scenario under consideration. The Feynman diagrams for pair and single production of VLQs are shown in Figs. 1–2.

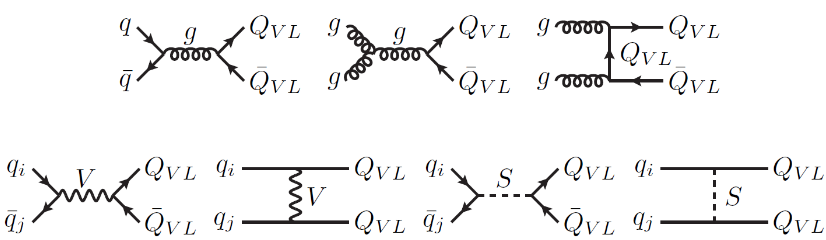

Fig. 1. Feynman diagrams for pair production of a generic VLQ. Above the dominant and model-independent QCD contributions, below the subdominant and model-dependent EW contributions.

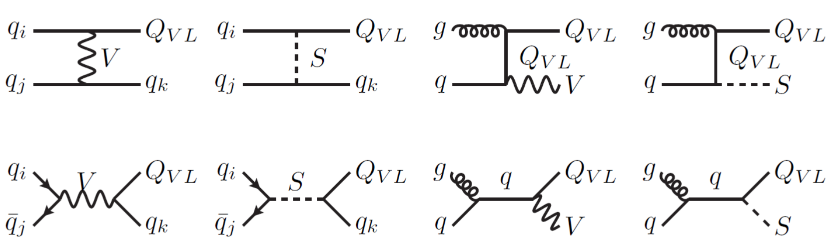

Fig. 2. Feynman diagrams for single production of a generic VLQ. VLQs can interact with SM quarks both through charged currents and neutral currents, allowing FCNCs also within SM states in diagrams with $q_i - q_j - \{V, S\}$ interactions.

4. Analysis of scenarios with multiple VLQs

Though recently experimental searches of QCD pair production and decays of VLQs have relaxed the hypothesis of exclusive decays in one channel, two common assumptions are still retained: (1) the signal of new physics is driven by only one vector-like quark at a time and (2) the vector-like quark can only interact with third-generation SM quarks. Though these minimal assumptions are reasonable, models of new physics, in general, predict a new *quark sector*, where VLQs may, in principle, couple not only to third generation SM quarks, but also to light generations. Therefore, the phenomenology of model that predicts the existence of VLQs is determined, in general, by the presence of multiple states with different charges, decaying, in principle, to either heavy or light SM states. The reinterpretation of mass bounds provided by experimental searches in terms of exclusion limits for a given scenario containing any number of new VLQs with generic mixing is therefore not straightforward. Considering a scenario with the presence, *e.g.*, of a B quark and of a X quark, and considering that they can both decay into the same final state $W^+W^-t\bar{t}$, the number of events in a search looking for same-sign dileptons will receive a contribution from both quarks, but with different kinematic properties, due to the fact that in one case the W^+t pair will reconstruct the X invariant mass, while in the other case the W^-t pair will reconstruct the B invariant mass. To perform a model-independent analysis of scenarios with multiple VLQs, only QCD pair production is considered, and the quarks are then supposed to decay promptly to SM states as $X \to W^+u_i$, $T \to \{W^+d_i, Zu_i, Hu_i\}$, $B \to \{W^-u_i, Zd_i, Hd_i\}$ and $Y_{-4/3} \to W^-d_i$, where $i = 1, 2, 3$ runs on SM families. The number of signal events surviving any given selection and kinematics cuts in a scenario containing any number of VLQs can be reconstructed by decomposing the full process into a sum of independent subprocesses involving all of the VLQs which are present in the scenario. Considering the efficiencies of each quark independently, it is possible to compute the surviving signal events for each species present in the given scenario and then determine the total number of signal events. The knowledge of the efficiencies can be obtained by performing simulations for each VLQ species and for different masses and branching ratios. The analysis can be limited to the minimal set of VLQ states that can decay directly into a SM quark plus an SM boson. Including more exotic states would involve the simulation of processes where VLQ chain decay to other new particles before getting to an SM final state: even if considering such processes would increase the accuracy of the determination of the number of signal events, neglecting them is a conservative approach, as all exclusion limits obtained with a lower number of signal events are, at worst, underestimated. With the final number of signal events it is then possible to compute the exclusion confidence level for any search channel, characterized by given numbers of background events and of measured events. The advantage for theorists is that the exclusion confidence level can then be translated in terms of excluded regions in the parameter space of the considered scenario. The advantage for experimentalists is that the implementation of different searches may help to determine the best way to be sensitive to yet unexplored scenarios and, therefore, put more conservative bounds on the masses of VLQs. A project dedicated to the implementation of this framework in a dedicated software is being developed: the determination of an efficiency database considering pair production of VLQs with different masses up to 2 TeV and testing the signal against direct searches of VLQs as well as SUSY-inspired searches is ongoing. The first results will be soon publicly available.

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