Vector-like Multiplets, Mixings and the LHC

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Abstract. Vector-like quarks are an essential ingredient of many extensions of the Standard Model of particle physics. Moreover the presence of more than one vector-like multiplet is a common situation in many models. The interplay of these vector-like multiplet with precision electroweak bounds, flavour and collider phenomenology, especially at the Large Hadron Collider is a important point for the discovery of physics beyond the standard model. I consider the presence of two vector-like multiplets in order to show the constraints on such scenarios from tree-level data and oblique corrections in the case of a completely general flavour mixings with all the three standard model families of quarks. I also describe a framework for studying the interplay of any number of vector-like multiplets.

1. Introduction
The Large Hadron Collider (LHC) in the recent years has confirmed the effective description of the electroweak sector given by the Standard Model (SM) Lagrangian with the discovery of the Higgs boson and the analysis of its properties. It has also allowed to obtain exclusion limits on new particles, which are in some cases quite constraining. However such constrains are often model dependent or rely on simplified assumptions. With the higher energy runs of the LHC it will be possible to refine these analyses and in many cases to tackle more realistic situations concerning the models of physics beyond the standard model. New vector-like (VL) fermions are often present in many of the extensions of the SM, especially in relation with the top sector, extra-dimensional models, little Higgs models, gauge-Higgs models, gauge coupling unification and models with an extended custodial symmetry. Both CMS [1] and ATLAS [2] have recently devoted a considerable effort in the analyses establishing bounds on this type of new particles. Initially, simplifying assumptions were considered (mixing only with the third generation of SM quark family or specific decay modes) [3, 4, 5, 6, 7, 8, 22, 9, 10, 11]. However the most recent analyses, due to larger data samples, allow exploring more general situations with mixing of VL quarks with the first two generation of SM quarks [12, 13, 14, 15].

Considering the presence of a complete multiplet of the symmetries of the Standard Model is however not enough in some realistic scenarios: in fact, theoretically justified models often contain multiplet of larger global symmetries which can be described in terms of several multiplets which are close in mass. The various multiplet are then mixed with each other via the Higgs interactions. The presence of general mixing structures and the interplay of different multiplets typically affects the tree-level and loop-level bounds, thereby modifying the results expected by performing simplified analyses based on a single particle or a single multiplet [16]. I will describe in the following the general structures and mixing of more than one VL quark...
multiplet and, specifically, the implications of the presence of two VL quark multiplets mixings with the 3 SM quark generation. I will also focus on a specific sub-set of scenarios where both VL multiplets contain a top partner and where eventual bottom partners (i.e. with electric charge $-1/3\,e$) do not mix with the SM down sector. This choice is done to minimise the constraints from flavour, which are very severe on mixing in the down sector only. Typically larger mixing are allowed in this case, providing larger single production cross sections at the LHC. These scenarios are also theoretically justified in models where the new physics couples dominantly to the top quark. Depending upon the multiplet considered, non-SM quarks, i.e. quarks having non-SM electric charge, may be present in the considered multiplets. I will estimate the constraints on such scenarios from electroweak precision (EWP) data (oblique and non-oblique) and current LHC data.

2. Vector-like multiplets

Minimal sets of VL multiplets, which mix with SM quarks and a SM (or SM-like) Higgs boson have been extensively studied in literature [17, 3, 10, 7, 12, 13]. In the following we shall distinguish three groups of multiplets as follows:

- top-type multiplets: multiplets containing one VL top partner but no bottom partners (i.e. no VL quark with electric charge $-1/3\,e$). In addition to a top partner these multiplets may contain quarks with exotic charges $5/3\,e$ and $8/3\,e$.
- bottom-type multiplets: multiplets containing one VL bottom partner but no top partners (i.e. no VL quark with charge $2/3\,e$). In addition to a bottom partner these multiplets may contain quarks with exotic charges $-4/3\,e$ and $-7/3\,e$.
- mixed multiplets: multiplets containing both VL top and bottom partners. In addition these multiplets may contain all of the exotic charged VL quarks.

In the following we shall focus on the top-type multiplets as phenomenologically interesting in many different models. The first few multiplets of this type are given in Table 1.

| Multiplet | $\psi$ | $(SU(2)_L, U(1)_Y)$ | $T_3$ | $Q_{EM}$ | Yukawa to SM |
|-----------|--------|-----------------|------|--------|--------------|
| Singlet 2/3 | $U$ | (1, 2/3) | 0 | $+2/3$ | Yes |
| Doublet 7/6 | $\left( \begin{array}{c} X^{5/3} \\ U \end{array} \right)$ | (2, 7/6) | $+1/2$ | $+5/3$ | Yes |
| Triplet 5/3 | $\left( \begin{array}{c} X^{8/3} \\ X^{5/3} \\ U \end{array} \right)$ | (3, 5/3) | $+2$ | $+8/3$ | No |
| | | | $+1$ | $+5/3$ | |
| | | | $0$ | $+2/3$ | |

Table 1. Quantum numbers for the top–type VL multiplets (up to triplets), explicitly indicating weak isospin, hypercharge, electric charge ($Q_{EM}$) and if a direct Yukawa coupling to SM quarks is allowed.

3. Vector-like quarks have chiral couplings to SM quarks

The structure of the couplings of the VL quarks to SM quarks and gauge bosons, in the case of an arbitrary number of VL representations, can be studied in a general way. Even in presence of mixing between various VL representations, the couplings are dominantly chiral like in the case of a single VL multiplet. Such couplings can be traced back to Yukawa couplings connecting the VL multiplets with a SM chiral fermion via the Higgs boson. This is true also for models with an extended Higgs sector: a singlet which acquires a VEV will generate masses in the form of VL
masses as it does not break the gauge symmetries; additional doublets will generate the same structures as the SM Higgs, and only the coupling of the Higgs boson may be affected; for larger representation, like a triplet, the VEV will generally induce large corrections to the $\rho$ parameter, thus it is bound to be very small and therefore generates small mixing terms. Following the above arguments, we can therefore state that our assumption of mixing mainly via the SM Higgs is solid. The Higgs in the SM is a doublet of SU(2), thus a field with weak isospin-1/2: a convenient way to classify the VL quarks is to use their weak isospin. VL multiplets with integer isospin (singlets, triplets, ...) can only couple via the Higgs to a left-handed doublet; on the other hand, VL multiplets with semi-integer isospin (doublets, quadruplets, ...) can only couple to a SM right-handed singlet. Also, one can potentially write a Yukawa coupling of a Higgs field with two VL quarks only if one of them has integer isospin (thus belonging to the first class) and the other semi-integer isospin. Of course, not all couplings are allowed as one needs to take into account the specific representation and the hypercharge. The FCNCs and the couplings between VL quarks and the standard ones are all proportional to the elements of the mixing matrices $V^\mu_{L/R}$, where $\alpha$ spans over the VL quarks, and $i = 1, 2, 3$ on the SM quarks.

Let us consider the most general case with $N - 3$ VL quarks that mix via Yukawa interactions to the SM quarks, and to each other. In the starting basis, we consider that the SM Yukawa matrices are already diagonal (for simplicity), while the VL masses are also diagonal. We consider $n_d$ semi-integer isospin states (doublets, ...) with potential mixing with the SM right-handed singlets, and $n_s = N - 3 - n_d$ integer isospin states (singlets, triplets, ... ) with potential mixing with the SM left-handed doublets. The most general mass matrix, therefore, will have the following block form:

$$
\mathcal{L}_{\text{mass}} = \bar{q}_L \cdot \left( \begin{array}{ccc|ccc} 
\mu_1 & 0 & 0 & 0 & \cdots & 0 \\
0 & \mu_2 & 0 & 0 & \cdots & 0 \\
0 & 0 & \mu_3 & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & M_4 & 0 & 0 \\
y_{4,1} & y_{4,2} & y_{4,3} & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & 0 & \cdots & 0 \\
y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} \\
0 & 0 & 0 & \omega'_{\alpha\beta} & M_{n_d+4} & 0 \\
\vdots & \vdots & \vdots & \vdots & 0 & \ddots \\
0 & 0 & 0 & 0 & 0 & M_N 
\end{array} \right) \cdot q_R + \text{h.c.} \quad (1)
$$

In this basis, the SM Yukawa masses $\mu_i$ are presented in a diagonalised form. We recognise the $3 \times n_s$ matrix $x_{i,\beta,\alpha}$ of the Yukawa couplings of the VL singlets/triplets (integer isospin), and the $n_d \times 3$ matrix $y_{\alpha,\beta,\gamma}$ of the Yukawa couplings of the VL doublets (semi-integer isospin). $M_\alpha$ represent the VL masses of all the new representations, while the $n_d \times n_s$ matrix $\omega_{\alpha,\beta,\gamma}$, and $n_s \times n_d$ matrix $\omega'_{\alpha,\beta,\gamma}$ contain the eventual Yukawa couplings among VL representations. In general the Yukawa couplings between VL quarks distinguish between the chiral components of the VL quarks, therefore in general $\omega' \neq \omega^T$: furthermore, $\omega'$ corresponds to the “wrong” Yukawa couplings, in the sense that it connects left-handed singlets (integer isospin) with right-handed doublets (semi-integer isospin), which is the opposite chirality configuration of SM Yukawa couplings. A detailed proof is given in the appendix of [13]. For the semi-integer isospin (doublet) VL quarks, the dominant mixing angle is right-handed, while the left-handed one is suppressed by an extra factor of $\omega'/M_{VL}$: the chiralities are exchanged for the integer isospin (singlets and triplets) VL quarks. It is interesting to stress that the subleading mixing angle is suppressed either by the “wrong” Yukawa couplings between VL quarks, $\omega'$, or by the light quark masses.

The leading mixing angle may be small in some cases, either because the relevant Yukawa coupling is absent or numerically small. However, in such a case, the couplings will receive an
extra suppression and the single production will become subdominant with respect to the pair production: for the pair production studies, only the branching ratios are relevant, independently on the chirality of the couplings.

4. Numerical results

In the following we shall consider few examples of the interplay among different VL multiplets and the SM (for a complete analysis see [16]). We have considered the mass parameters $M_1$ and $M_2$ of the VL quarks to be same, i.e. $M_1 = M_2 = M$. As the models have too many parameters to make a meaningful scan, we will show results in two limiting cases, when possible:

- the VL quarks can mix with a single SM generation, but not with each other (i.e. $\omega \sim \omega' \ll M$);
- the VL quarks mix with each other (wherever possible), but the mixing with SM quarks is very small.

The results in these simple limits can give a general idea on the allowed value of the mixing parameters, even though the case where all of them are non-zero is more realistic. We will focus on the benchmark value for the VL mass of 800 GeV as a recent CMS analysis [23] sets a bound of 788 GeV under the assumption of strong pair production of VL quarks and 100% branching fractions to $qW$. In the following we also consider cases in which the VL quark does not decay to $qW$. For these cases the bound does not apply directly, but these VL quarks are in doublets containing also other VL quarks for which the bound applies. As it is reasonable to assume that mass splittings inside multiplets are not large compared to the mass scale of the multiplet, we shall apply this 800 GeV benchmark value to all cases.

4.1. Singlet $Y = 2/3$ and Doublet $Y = 7/6$

![Figure 1. Singlet $Y = 2/3$ and Doublet $Y = 7/6$: EWP bounds at 1 $\sigma$ (red-dashed), 2 $\sigma$ (green-dashed) and 3 $\sigma$ (blue) for VL quarks coupling with the first (left panel) and third (right panel) SM generations, compared with the region excluded at 3$\sigma$ by tree-level bounds (yellow region). Here, $M = 800$ GeV, and $\omega = \omega' = 0$. Only the first quadrant is shown as the figures are symmetric with respect to a sign change in the coordinates in the other 3 quadrants. Similar considerations apply to all the other figures of the same type.](#)

This scenario contains – besides the SM particle spectrum – two VL top quarks and one exotic quark with charge $5/3$. The additional parameters (apart from the SM ones) are: $x^k_2$, $y^k_1$, 

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Figure 2. Singlet $Y = 2/3$ and Doublet $Y = 7/6$ EWP bounds at $1\sigma$ (red-dashed), $2\sigma$ (green-dashed) and $3\sigma$ (blue) as a function of the new Yukawa couplings $\omega$ and $\omega'$ with $M = 800$ GeV. We have assumed that there is no mixing of VL quarks with the SM quark generations i.e. $x_2^k = y_1^k = 0$.

$\omega$, $\omega'$ and $M$ with $k$ running on SM quark generations. We first study the case where $\omega' \sim \omega \sim 0$, and the VL quarks couple to a single generation: in this case, setting $\omega'$ to zero allows us to set both Yukawa couplings $x_2$ and $y_1$ to be real and positive. The allowed regions in the parameter space, given the constraints from tree-level and EWP tests, are presented in Figure 1. We see that for couplings to the light generations, the tree level bounds always dominate, and require the mixing of VL quarks to be rather small. The case of the third generation is very different: the tree level bounds are very weak as they only come from $V_{tb}$, while EWP tests allow for large mixings, especially via a compensation between the doublet and singlet (in particular, $y_3^1$ can assume very large values). This situation can be very interesting in the single-production channel, where for instance the top partner may be produced via couplings to the first generation (the smaller coupling is easily compensated by the valence quark in the initial state [13]) and then decay into a third generation quark [18, 19, 20].

In Figure 2 we show the EWP bounds in the plane of the Yukawa couplings between VL quarks, $\omega$ and $\omega'$, assuming that the other couplings are small. This plot gives a general idea on the allowed size of $\omega$ and $\omega'$: the bound is indeed not very strong, and values up to 300 GeV are allowed. The plot is clearly symmetric under change of sign of either $\omega$ or $\omega'$, reflecting the one arbitrary phase in this sector. As we are approximately decoupling the two $t'$s from the SM quarks, the mixing is dominated by the $2 \times 2$ block of the VL quarks. The mixing angles vanish when $\omega = -\omega'$, thus explaining the sharp dents in the excluded region. This effect only appears in our limiting choice $M_1 = M_2$ and for negligible mixing to SM quarks.

4.2. Doublet $Y = 1/6$ and Doublet $Y = 7/6$

This scenario is of particular interest as it corresponds to a bi-doublet of the custodial SO(4) symmetry, which is a basic ingredient for top partial compositeness in models of composite Higgs (see [22]). It contains two VL top quarks, one VL bottom quark and one exotic quark with charge 5/3. The additional parameters are: $y_1^k$, $y_2^k$ and $M$ with $k$ running on SM quark
generations. Note that for this case, mixing between VL quarks (i.e. $\omega$ and $\omega'$) is not allowed. This model also introduces an additional mixing in the bottom sector, which is independent from the mixing in the top sector. It is therefore possible to impose the condition $y_{1d} = 0$ without affecting the top sector.

The results for the combined tree-level and EWP bounds are given in Figure 3. For the first generation, there is an interesting cancellation in the tree-level bounds for $|y_{11}| = |y_{12}|$: this is a consequence of an enhanced custodial symmetry, and this fact has been used in the literature to justify $O(1)$ mixings of VL quarks with light generations [21]. EWP bounds show a similar cancellation, however along an axes which is a bit off compared to $|y_{11}| = |y_{12}|$, therefore a tension between the two allowed regions develops for large mixings. A similar behaviour in the EWP bounds can be seen in the case of mixing to the third generation only.

4.3. Single production cross sections

Tree-level, loop-level and the bounds from single production processes at the LHC can be compared for the cases discussed above. The relevance of single production is given by the fact that its cross-section depends on both the masses of the VL quarks and their couplings to the SM quarks; moreover, it is well known that single production becomes the dominant channel at the LHC, overcoming QCD pair production, when quark masses are higher than a certain (model-dependent) value. For typical scenarios where VL quarks mix predominantly with third generation and mixing parameters are not too constrained by flavour physics and EWP tests, the mass bounds from QCD pair production are already in the region where the single production channel is relevant or even dominant [12]. So far, few experimental searches for single production of VL quarks have been performed. To be specific, in the following we will consider the single production of a VL top partner in association with a light jet, and the mass of the VL quark will be fixed to 800 GeV. We consider exclusive coupling to each of the three SM generations for each scenario. In Figure 4, the tree-level bounds are the most stringent ones if VL quarks mix to the light generations, and they are stronger than the current bound form the ATLAS search. In both cases, the largest $T jet$ cross section allowed is between 0.5 and 1 pb. In the case of mixing to the third generation only EWP and tree level bounds conspire to

Figure 3. Doublet $Y = 1/6$ and Doublet $Y = 7/6$ EWP bounds at 1\(\sigma\) (red-dashed), 2\(\sigma\) (green-dashed) and 3\(\sigma\) (blue) for VL quarks coupling with the first (left panel) and third (right panel) SM generations, compared with the region excluded at 3\(\sigma\) by tree-level bounds (yellow region in the left panel). $M = 800$ GeV, $\omega = \omega' = 0$. 

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select small mixing, and the single production at 14 TeV is limited to small values around 100 fb. in Figure 5 the results for the “Doublet \((Y = 1/6)\) and Doublet \((Y = 7/6)\)” scenario are presented. Again, though the presence of an exotic quark with charge 5/3 and of right-handed charged currents which contribute to the corrections to the oblique parameters, the tree-level constraints are stronger for the most part of the parameter space.

Figure 5. Doublet \(Y = 1/6\) and Doublet \(Y = 7/6\) for mixing with first generation only (left), second generation only (middle), third generation (right), and for a mass of the VL quarks of 800 GeV. The channel is T+jet. The grey contour lines correspond to cross-section values in picobarns at 14 TeV (this channel is not allowed in the case of the plot on the right). The region inside the red line is allowed by the S and T parameters. The region inside the blue line is allowed by the tree-level bounds. The dashed black lines are the bounds from the ATLAS search.

5. Conclusion
In most models beyond the SM, VL quarks appear in complete multiplets and usually more than one multiplet is present. In this analysis we have considered scenarios with multiple VL quarks both from the point of view of the general mixing structure with the three Standard Model generations and considering the mixing pattern of these multiplets for the determination of mixing effects and precision electroweak observables both at tree-level and at loop-level. The
specific case of two different vector-like quark multiplets has been discussed in detail, with a special focus on an example containing top partners. The main result is that tree-level and loop-level constraints provide complementary information. Moreover the interplay of the vector-like multiplets among themselves and with the Standard model quarks have important consequences for phenomenology as in some cases large single production cross-sections are possible and coupling with light generations is not necessarily suppressed. These results have phenomenological implications for LHC searches as the bounds we have extracted pinpoint particular regions of the parameter space and suggest that in realistic cases containing multiple multiplets of vector-like quarks, cancellations are possible from tree-level bounds which allow large values of the mixing parameters. Direct searches by the LHC experiments in the near future will play a major role in studying physics beyond the Standard Model with VL multiplets.

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