Single production of vector-like quarks with large width at the Large Hadron Collider

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Abstract

Vector-Like Quarks (VLQs) are predicted by several theoretical scenarios of new physics and, having colour quantum numbers, can copiously be produced at the Large Hadron Collider (LHC), so long that their mass is in the testable kinematic regime of such a machine. While it would be convenient to assume that such objects are narrow and can be treated in the so-called Narrow Width Approximation (NWA), this is not always possible, owing to the fact that couplings and particle content of such new physics scenarios are not generally constrained, so that a large value of the former and/or a large variety of VLQ decay channels into the latter can contribute to generate a large decay width for such extra quarks. We have addressed here the issue of how best to tackle in LHC analysis the presence of large (and model-dependent) interference effects between different VLQ production and decay channels as well as between these and the corresponding irreducible background. We have confined ourselves to the case of single production of VLQs, which is rapidly becoming a channel of choice in experimental searches owing to the ever increasing limits on their mass, in turn depleting the yield of the historically well-established double production channel. Indeed, this poses a further challenge, as the former is model-dependent while the latter is essentially not. Despite these conditions, we show here that an efficient approach is possible, which retains to a large extent a degree of model independence in phenomenological studies of such VLQ dynamics at the LHC.

Keywords: Extra quarks, vector-like quarks, LHC, large width, single production, interference

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1 Introduction

There is no reason why additional heavy quarks may not exist in Nature: clearly, though, these ought to be heavier than the top quark. However, following the discovery of a Higgs boson at the Large Hadron Collider (LHC) \(^{112}\) closely resembling the one embedded in the Standard Model (SM), the existence of a fourth generation of chiral quarks (i.e., with SM-like \(V \sim A\) structure in gauge boson charged currents) has been disfavoured \(^{33-44}\). A possibility for the existence of additional heavy quarks, even in the presence of a SM Higgs sector, is afforded by Vector-Like Quarks (VLQs), i.e., heavy spin 1/2 states that transform as triplets under colour but, differently from the SM quarks, their Left- and Right-Handed (LH and RH) couplings have the same Electro-Weak (EW) quantum numbers.

VLQs are predicted by several theoretical constructs: e.g., models with a gauged flavour group \(^{9,12}\), non-minimal Supersymmetric scenarios \(^{15,18}\), Grand Unified Theories \(^{19,20}\), little Higgs \(^{21,22}\) and composite Higgs \(^{23,30}\) models, to name but a few. In most of these frameworks VLQs appear as partners of the third generation of quarks, having an EW coupling to top and bottom quarks. They are accessible at the LHC detectors in a variety of final states \(^{31-35}\), some of these already explored by the ATLAS and CMS collaborations \(^{36-44}\).

Up to now, experimental searches have been designed based on a simplified scenario for modelling the VLQ dynamics, assuming that only one new VLQ is present beyond the SM and parameterising its production, cross-section (\(\sigma\)), and decay, Branching Ratio (BR), rates using the Narrow Width Approximation (NWA) \(^{30,41}\), with the exception of \(^{42,43}\) where large width scenarios were also considered. In reality, both aspects need not be true. On the one hand, most of the aforementioned VLQ models predict in general the existence of a new quark sector, which implies the presence of more than one new coloured state. The possibility of reinterpreting experimental data in the context of scenarios with multiple VLQs has been addressed in \(^{45,46}\). Furthermore, especially when such states are (nearly) degenerate in mass, significant interference effects amongst VLQs may occur that would alter the overall yield \(^{47}\). On the other hand, VLQs can have a large width, both in virtue of their mass (much larger than the top quark one) and the variety of decay channels they can undergo, including neutral current ones: contributions from large widths can in turn lead to significant effects, also induced by interferences with the irreducible background, onto the sensitivity of current experimental analyses. Analyses of large width effects in the case of VLQ pair production, i.e., even when the VLQ production stage is due to QCD interactions only, have been performed in \(^{48,49}\) (see also \(^{50,51}\)).

In this paper we consider singly produced VLQs mixing with either third or light generations of SM quarks. Unlike VLQ pair production, wherein the case of mixing with third generation quarks is induced solely by model-independent QCD interactions while the one with light generations also sees a generally subleading (because quark-antiquark induced) EW component, all processes yielding single VLQs in the LHC proceed via model-dependent EW interactions which enter already at the production level connecting the production rate to the aforementioned large width and interference effects. In order to interpret the limits of an experimental search on a given range of cross-sections one must determine the size of the VLQ couplings which generate such cross-sections. If the couplings are large, finite width effect and/or interference effects may be not negligible, and it becomes imperative to take them into account in the experimental searches. The exact relation between the EW couplings and those effects is rather model-dependent, resulting on many possibilities for signal modelling. In this paper, we propose strategies for presenting the results of experimental analyses in a simple, though solid, model-independent framework, allowing a straightforward re-interpretation of experimental data. A similar approach has been already used in its simplest form in Refs. \(^{12,43}\). Such strategy should limit the need of performing numerical recasting for the reinterpretation of results: the possibility of having ways to avoid numerical recasting (when possible) is becoming pressing as experimental searches rely more and more upon numerical frameworks which cannot be easily reproduced in tools for phenomenological analyses, such as boosted decision trees or multi-variate analyses.

The plan of the paper is as follows. In Section \(2\) we describe the analytical model-independent parameterisation and we discuss the issues induced by interference contributions. In Section \(3\) we perform the phenomenological analysis: first, in Section \(3.1\) we set up our framework, then, in Section \(3.2\) we undertake a numerical recasting of a CMS search to obtain bounds for VLQs with large width, finally, in Section \(3.3\) we adopt an analytical parameterisation and compare it to numerical results, also discussing how to treat interference in a specific benchmark. In the final section we draw our conclusions.

\(^{1}\)If the Higgs sector is enlarged with respect to the SM to contain additional (pseudo)scalar states \(^{5,7}\), or if more than one heavy quark multiplet is introduced \(^{8}\), new chiral quarks are allowed.
2 Model-independent parameterisation of the cross-section

Apart from the aforementioned small contamination due to EW interactions in the case of mixing with light quarks, in processes of VLQ pair production, the VLQs are produced through their QCD couplings to the SM gluons and subsequently decay to the SM quarks through couplings induced by their mixing which, together with the mass of the VLQs, are the free parameters of the Beyond the SM (BSM) physics scenario under consideration. The advantage, from a phenomenological point of view, of pair production processes is thus given by the fact that the production of VLQs is essentially only dependent upon their mass, as the QCD coupling is a SM parameter unmodified by new physics.

In processes of VLQ single production, in contrast, the same type of couplings which induce the VLQ decays also determine the production rate, i.e., the cross-section of single VLQ production processes depends on their couplings to SM quarks, irrespectively of their mixing patterns. The size of such couplings determines for which VLQ mass the cross-section of single production becomes dominant with respect to pair-production at a given collider energy. Moreover, such couplings also contribute to the partial width of the VLQ in their decay channels to SM states. The total width of the VLQ, however, can be increased not only by increasing the couplings of the VLQ with SM quarks and bosons, but also by including further decay channels to other new physics states. In the case of a VLQ with large width, the latter hypothesis is preferable from a phenomenological point of view, as large couplings of VLQs with SM quarks are in general strongly constrained by oblique observables and Higgs couplings \[18,52\]. To perform an analysis of single production of VLQs with large width it is essential to separate the effects which are purely due to the large width from the dependence of the cross-section on the VLQ couplings. As we shall see, in the context of our analysis, such a goal can be achieved considering a suitable parameterisation which factors out the contributions of different couplings.

But let us now proceed to define the constituent processes of VLQ production in single mode. In essence, herein, we consider any topology leading to a three-particle final state made up by SM objects only which contains at least one VLQ propagator. A subtlety, however, arises when deciding upon the initial state. In fact, single production of VLQs can be studied either by considering the proton to be constituted of five quark flavours, the so-called 5-Flavour Scheme (5FS), or else assuming that bottom quarks are not in the initial state but can only appear from gluon splitting, i.e., the 4-Flavour Scheme (4FS). Any phenomenological difference between 4FS and 5FS would vanish if it was possible to describe the processes at all orders in QCD perturbation theory.\[\text{In our analysis we will work in the 5FS, for which the topologies are represented in Fig.~1. (Notice that some of these only exist in the Large Width (LW) regime, not in the NWA.)}\] This choice is simply dictated by the preliminary results of Ref.\[54\] (Contribution 3), which show that, for a specific process and in the NWA, when kinematical distributions of final state objects computed at LO in the 5FS exhibit sizeable differences with respect to those computed at LO in the 4FS, the distributions obtained through a NLO description of the process are closer in shape to the LO results in the 5FS.

The total cross-section (\(\sigma\)) can be parameterised by factorising the BSM couplings considering a reduced quantity, labelled as \(\hat{\sigma}\), analogously to what was done in \[34\]. In the absence of any kind of interference between different topologies, the model-independent \(\hat{\sigma}\) depends only on the mass and total width of the VLQ. The factorisation of the signal cross-section (labelled with the subscript \(S\) in the following) can be written as (see Fig.\[1\]):

\[
\sigma_S(C_1, C_2, M_Q, \Gamma_Q) = C_1^2 \ C_2^2 \ \hat{\sigma}_S(M_Q, \Gamma_Q),
\]

where \(C_1\) and \(C_2\) are the couplings corresponding to the interactions at both sides of the \(Q\) propagator, and \(\Gamma_Q = \Gamma(C_1, M_Q, m_{\text{decays}})\) is the total width of the VLQ, which depends on its mass, the masses of all its decay products and the couplings through which the VLQ interacts with all the particles it can decay to, including (but not exclusively) \(C_1\) and \(C_2\).

This parameterisation cannot be generalised if interference contributions amongst signal components that contain different coupling content and/or with SM background are non-negligible. In this case the cross-sections for the pure signal and its interference contributions with the irreducible background are written as \(\sigma_S\) and \(\sigma_{SB}^\text{int}\), where the second represents the interference amongst signal (\(S\)) topologies or with the SM background (\(B\)). In Fig.\[2\] it is shown an example for the \(Wb\) final state: in this case \(\sigma_S = \sigma_W + \sigma_{WB}^\text{int}\) and \(\sigma_{SB}^\text{int} = \sigma_{WB}^\text{int} + \sigma_{Zb}^\text{int}\), where the subscript of each term represents the bosons propagating in the corresponding topologies. The individual terms of the sum are not necessarily gauge invariant, while the observable quantities \(\sigma_S\) and \(\sigma_{SB}^\text{int}\) are.

\[\text{For specific details we refer to the wide literature on this subject (see for example \[53,55\] for single top production).}\]
Figure 1: Complete list of the generic topologies for final states compatible with single VLQ production in the 5FS. Topologies on the left column can be described in both the NWA and LW regimes while topologies on the right column are neglected in the NWA approximation. Here, \( V \) represents the \( W \) and \( Z \) bosons of the SM.

Figure 2: Example on the left of a subset of interfering topologies in the process \( bb \rightarrow bW^+\bar{t} \) mediated by a \( T \) VLQ and different SM bosons. The diagrams on the right show analogous contributions from the SM background, which interferes with the signal.

The only possible factorisation in case interference terms are not negligible is:

\[
\sigma_S(C_1, \ldots, C_2, M_Q, \Gamma_Q, \chi_Q) = C_2^2 \tilde{\sigma}_S(C_1, \ldots, M_Q, \Gamma_Q, \chi_Q) \quad \text{and} \quad \sigma_{SB}^{\text{int}} = C_2^2 \tilde{\sigma}_{SB}^{\text{int}}(C_1, \ldots, M_Q, \Gamma_Q, \chi_Q),
\]

where \( C_2 \) is the coupling corresponding to the interaction between \( Q \) and the boson in the final state, \( C_1 \) are the couplings through which \( Q \) interacts with the different virtual bosons and \( \chi_Q \) the dominant chirality of the VLQ couplings, which can be LH or RH depending on the VLQ representation and for total rates only plays a role in interference terms. As an example, a \( T \) singlet will decay through charged current to a bottom quark with a dominantly LH chirality \([34, 35]\) whereas a \( T \) as part of a doublet will produce a dominantly RH bottom: the interference with the SM background, for which the bottom quark can only be produced with LH chirality through charged currents, will be different in the two scenarios.

In the limit of negligible interference between different signal topologies, the pure signal contribution can be approximated as:

\[
\sigma_S(C_1, \ldots, C_2, M_Q, \Gamma_Q) \sim C_2^2 \sum_i \tilde{\sigma}_S(C_1, i, M_Q, \Gamma_Q),
\]

where the potentially gauge-dependent contribution is assumed to be negligible as well.

A further limit is represented by scenarios in which the VLQ interacts exclusively with one SM boson. In this case, besides recovering Eq. (1) for the cross-section of the pure signal contribution, the interference with SM background can be written as:

\[
\sigma_{SB}^{\text{int}}(C_2, M_Q, \Gamma_Q, \chi_Q) = C_2^2 \tilde{\sigma}_{SB}^{\text{int}}(M_Q, \Gamma_Q, \chi_Q).
\]
the reinterpretation is made does not contain sizeable interference terms of any kind for the considered final state. Such parameterisation, when associated with a proper way to interpret experimental results, discussed below, represents a robust model-independent framework for testing any theoretical scenario predicting VLQs with small or large width against experimental limits in a given channel. This approach has been followed in two CMS analyses [42,43], where $\hat{\sigma}$ was used for an interpretation of experimental results for single production of VLQs with large width. The values of $\hat{\sigma}_S$ and $\hat{\sigma}_B^{\mathrm{int}}$ in Eqs. (2) to (4), however, contain a further model-dependency, represented by the impossibility to factorise the $\{C_{1,\ldots}\}$ couplings in a gauge-invariant way. If interference terms are sizeable, this is an unavoidable consequence and the analysis would have in any case a limited reinterpretation applicability.

Both parameterisations can be easily generalised to compute cross-sections at NLO in QCD, as the factorisation of the EW couplings to derive the $\hat{\sigma}$’s is not affected by the contribution of radiative QCD effects. A NLO calculation of single production of VLQs with finite width is however beyond the scope of this paper.

3 Phenomenological analysis

In this section we will provide case studies for the reinterpretation of experimental results of searches for single production of VLQs with finite width, comparing the bounds obtained through a numerical recasting with the results obtained applying the analysis strategies of Sect. 2.

3.1 Benchmarks

Analogously to what has already been done in the CMS analyses [42,43], we will consider specific and representative scenarios for the interactions of VLQs with the SM states. Couplings between VLQs and SM quarks and bosons are parameterised as:

$$c_Z = \frac{e}{2c_w s_w} \kappa_Z, \quad c_W = \frac{e}{\sqrt{2} s_w} \kappa_W \quad \text{and} \quad c_H = \frac{M_Q}{v} \kappa_H,$$

(5)

where $v = 246$ GeV is the Higgs Vacuum Expectation Value (VEV), $c_w$ and $s_w$ are the cosine and sine of the weak angle $\theta_w$ and $\kappa_{W,Z,H}$ are coupling strengths. In the limit where only one VLQ representation is present in Nature and the particles are narrow the $\kappa$ parameters accurately approximate the sine of the mixing angle between VLQ and SM quark (for a relation between couplings and mixing angles see, e.g. Ref. [52]). In the NWA, if the VLQ is a singlet, the coupling parameters are related as $\kappa_Z \simeq \kappa_H \simeq \kappa_W \simeq \kappa$ while, if the VLQ is within a doublet (and assuming that the Yukawa coupling of the other element of the doublet is zero), the coupling parameters become $\kappa_Z \simeq \kappa_H \simeq \kappa$ and $\kappa_W \simeq 0$. These relations are not satisfied in the large width regime.

Minimal extensions of the SM with one unique VLQ representation where the VLQ has large couplings are excluded by other constraints (such as EW precision tests or corrections to SM couplings) [48,52]. In our case study the large width regime will be achieved by considering the total width as a free parameter but imposing for VLQ singlets and doublets identical relations between the $\kappa$ parameters as in the NWA. We also consider more extreme scenarios where we assume 100% couplings of the VLQ with each of the SM bosons. A summary of the benchmarks we consider is reported in Tab. 1. Through this procedure the assumption of a minimal model is relaxed: new physics, in the form of mixings either in the quark or bosonic sectors due to additional representations of VLQs or new gauge bosons or scalar fields, must contribute to generate the relations between couplings.

| $100\% W$ | $100\% Z$ | $100\% H$ | Singlet-like | Doublet-like |
|----------|----------|----------|--------------|--------------|
| $\kappa_Z^q = \kappa_H^q = 0$ | $\kappa_W^q = \kappa_H^q = 0$ | $\kappa_W^q = \kappa_Z^q = 0$ | $\kappa_W^q = \kappa_Z^q = \kappa_H^q = 0$ | $\kappa_W^q = 0$ and $\kappa_Z^q = \kappa_H^q$ |

Table 1: Benchmark points and corresponding coupling relations.

The event generation has been performed through MadGraph5-AMC@NLO [57,58] using the NNPDF3.0 PDF set [59] at LO with $\alpha_S = 0.118$ and setting the QCD renormalisation and PDF factorisation scales to the mass of the VLQ. The generated events have been subsequently processed through Pythia 8 [60,61] to include parton showering and hadronisation. Finally, the hadronised events have been analysed through MadAnalysis 5 [62], which uses Delphes 3 [63] for the emulation of detector
The VLQ model used for the simulation was implemented in FeynRules \cite{FeynRules} to obtain the UFO \cite{UFO} model format to be used inside MadGraph5_AMC@NLO. This model is a slightly modified version of the public model described in \cite{VLQmodel} where each coupling of the VLQ has been assigned a different label in order to isolate individual interference contributions through the MadGraph5_AMC@NLO syntax `COUPLING\_ORDER^2==N` in the process of diagram generation, where the `i`th coupling order is counted `N` times in the squared amplitudes, making it possible to generate separately each term of Eq. \eqref{eq:VLQ}. It is not within the scope of this paper to investigate the impact on searches due to the choice of the proton scheme. However, as most of the experimental searches performed so far adopt the 4FS (including the one recast in this analysis) a more quantitative discussion about the choice of the flavour number scheme is in order. As an example, in Fig. \ref{fig:pt_bjet} we show the $p_T$ distribution of the leading $b$-jet comparing the 4FS and 5FS at LO for a $B$ VLQ mixing with third generation, in different width regimes, for the processes $pp \to tWj$ and $pp \to bZj$. The dependence of the distributions on the width of the VLQ can be sizeable, thus potentially affecting the efficiency of experimental cuts. The final state $b$-quark is dominantly generated in the $B$ decay and therefore is fairly central in both 5FS and 4FS in any width regime. The width-dependent differences in the shapes are generally of similar size in both 4FS and 5FS.

The signal cross-sections are generally of similar size between 4FS and 5FS in the NWA at LO \cite{CrossSection}. We had also checked that in all parameter space we probe the cross-sections calculated in the 4FS are always smaller than the ones calculated on the 5FS. Therefore, the interpretation of results in terms of number of events in the 4FS acts as a lower bound to the a more realistic exclusion bound.

\subsection*{3.2 Recasting and reinterpretation of experimental data}

As a representative analysis for the recast of experimental data, the CMS search CMS-B2G-16-006 \cite{CMSB2G} has been chosen. This analysis specifically targets a heavy VLQ with charge $+2/3$ or $-4/3$ decaying into a $b$-quark and a $W$ boson, which is produced singly in association with a light flavour quark and a $b$-quark. Thus, in the 4FS, the considered process is $pp \to T(\to W b) b j$. The search selects events with one lepton (electron or muon in two different signal regions) and at least two jets, one central ($b$-tagged) and one forward. A set of kinematical cuts are also imposed, and we refer to \cite{CMSB2G} for all the relevant details. In table \ref{tab:recast} we compare the efficiencies obtained by our recast implementation with the ones reported by \cite{CMSB2G} under the same signal assumptions of the experimental search. We stress that, for the purposes of this study, we are not interested in an overly precise reconstruction of the experimental results: our intent is to achieve a realistic analysis framework to demonstrate how to reinterpret experimental data in scenarios where the VLQs have a large width.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{pt_bjet.png}
\caption{Distributions of the transverse momentum of the leading $b$-tagged jet for two processes. Left panel: $pp \to tWj$ (in the 5FS) or $pp \to tWjb$ (in the 4FS); right panel: $pp \to bZj$ (in the 5FS) or $pp \to bZjb$ (in the 4FS), with subsequent on-shell decays of the SM states in both cases. The comparison is made for a $B$ mass of 1200 GeV and for different values of the width-over-mass ratio ($\Gamma_Q/M_Q$) of the VLQ.}
\end{figure}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Process & 4FS & 5FS \\
\hline
$pp \to tWj$ & & \\
$pp \to bZj$ & & \\
\hline
\end{tabular}
\caption{Comparison of the efficiencies obtained by our recast implementation with the ones reported by CMS-B2G-16-006 for the CMS search CMS-B2G-16-006.}
\end{table}
Table 2: Comparison of the experimental and recasted efficiencies for the different signal regions for a \( pp \rightarrow T(\rightarrow Wb)jb \) signal in the 4FS with \( m_T = 1000 \) GeV in the NWA.

| Channel     | Experimental | Electron | Muon | Total |
|-------------|--------------|----------|------|-------|
|             |              | 1.3%     | 1.4% | 2.7%  |
| Recasting   | 0.98%        | 1.31%    | 2.29%|       |

We recast this analysis for the large width case by scanning the \( \Gamma_Q/M_Q \) from, e.g., 1% to 40% in steps of 5% and \( M_Q \) from 600 to 2000 GeV in steps of 100 GeV. Four processes will be considered: the original target of the search (a third generation \( T \) partner in the \( pp \rightarrow Wbq \) channel) but also a third generation \( B \) partner in the \( pp \rightarrow Wtt \) channel, and a light generation \( T \) and \( B \) partner on the \( pp \rightarrow W\bar{q}q \) channel (notice that, as we consider the 5FS, a \( q \) may also be a \( b \)). For the sake of linearity, we first show the results of the recast in the \( pp \rightarrow Wbq \) channel. The values of the the largest allowed observed cross-section at 95% Confidence Level (CL) on the \( (M_Q, \Gamma_Q/M_Q) \) plane that we obtain for this channel are shown in Fig. 4.

![Figure 4: 95% CL largest allowed cross-sections (in pb) for the \( Wbq \) final state as a function of \( m_T \) and of \( \Gamma_T/m_T \) for a VLQ \( T \) coupling to the third SM quark generation and decaying 100% to \( bW \).](image)

To interpret the results with the benchmarks of Tab. 1 we saturate the values of the VLQ couplings to obtain the needed size of the width for each point in the \( (M_Q, \Gamma_Q/M_Q) \) grid of our scan. The total cross-section obtained by saturation is then compared to the experimental limits and it is verified to be excluded or not. In fact, the coupling necessary to fix \( \Gamma_Q/M_Q \) have an effect on the cross-section of the process and therefore on the region of exclusion on the \( (M_Q, \Gamma_Q/M_Q) \) plane, using the same data. For instance, trivially, the value of the VLQ couplings will be larger for benchmark points where they interact 100% in a specific channel than for the singlet- or doublet-like benchmarks, given the contribution from other decay channel(s) in the latter case.

This done in Fig. 5 where we show the value of the \( Wbq \) signal cross-section as a function of the VLQ mass and of its \( \Gamma_Q/M_Q \) ratio, together with the 95% exclusion line for the \( Wbq \) final state. It is possible to notice that the NWA region is not excluded while the exclusion range appears as \( \Gamma_Q/M_Q \) increases, thus highlighting the phenomenological impact of the \( LW \) regime. The shape of the exclusion boundary is a balance between how the theory cross-section grows on the \( (M_Q, \Gamma_Q/M_Q) \) plane and the behaviour of the signal kinematics. In Fig. 5 we see that the exclusion bounds roughly track the variation of the cross-section, with the exclusion line in the region where the cross-section is slightly larger than 1 pb. Such behaviour is related to the fact that, for the considered CMS search, selection cuts are designed in such a way that the signal efficiencies vary only moderately in the whole plane. In the light of this result, in the following, we will only show results for VLQ coupling which are 100% to a specific SM boson, the results for singlet- and doublet-like cases being qualitatively analogous to a simple rescaling of the cross-section.
Figure 5: Cross section (in pb) for the $Wbj$ final state as a function of $M_T$ and of $\Gamma_T/M_T$ and 95% exclusion line (in black) for a VLQ $T$ decaying 100% to $bW$ (left panel) or singlet-like (right panel).

In Fig. 6 we show the values of the the largest allowed cross-section at 95% CL, together with the exclusion bound, for each point of the grid in the $(M, \Gamma_Q/M_Q)$ plane for a VLQ $T$ (top row) or $B$ (bottom row) coupling to the first (top and bottom-left panels) or third (bottom-right panel) SM quark generations. For the scenario where the $B$ couples with the third SM quark generation (bottom-right) the value of the the largest allowed cross-section is rather large in comparison with the other benchmarks we consider and therefore no exclusion can be made. In contrast, we do find exclusion regions for the $Wjj$ channel mediated by a light generation $T$ or $B$ partner.

Analogously to the $Wbj$ case, the exclusion lines in both the $Wjj$ scenarios basically follow the increase of the cross-section due to the increase of the coupling. However, as the search is not optimised for $Wjj$ final states, the largest allowed cross-section is much larger than for the $Wbj$ case. The fact that we still get a similar exclusion for these final states is due to the higher cross-section for the light generation VLQs: PDF effects makes the $b$-initiated processes less likely than the $u$- and $d$-initiated ones, leading to a much larger cross-section for the $Wjj$ final states. Between the two $Wjj$ plot results, we observe a stronger exclusion in the case of the propagation of a $B$ VLQ, rather than a $T$ VLQ, due to the fact that the cross-section is larger while the efficiencies are similar in the whole parameter space.

In all the channels we consider the largest allowed cross-section decreases when the mass increases, but, except for small masses (less than 1 TeV), this search is not really sensitive to the width variation. The effect of the width on the excluded cross-section is larger for $M_Q \approx 600$ GeV where it can increase by a factor 4 with $\Gamma_Q/M_Q$ increasing from the NWA to $\approx 40\%$. The overall weak dependence of the results on the VLQ width is related to the fact that the kinematic distributions of the final states are also often weakly affected. The same weak dependence was found in the two CMS single production searches exploring the large VLQ width regime [42,43].

3.3 Reinterpretation through the reduced cross-section $\hat{\sigma}$

In this section we provide an example of how to interpret experimental data only using the reduced cross-section $\hat{\sigma}$ described in Sect. 2 for a model featuring a VLQ interaction with SM bosons with given couplings, mass and total width. The procedure can be generalised for any search of BSM states which can decay into SM final states, for which the width of the resonance can be considered as a further degree of freedom, complementary to the mass of the BSM state, for the determination of the maximum excluded cross-section.

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3This can be explained by a combination of two factors: the final state $Wtt$ is heavier than the other ones we consider, leading to a much smaller cross-section and, since the search is not targeting this specific final state, the signal efficiencies are smaller than for the other channels.

4For instance, the search we are recasting requires a $b$ quark in the final state, which can only come from the accompanying jet when the VLQ only decays to light quarks.
If interference terms, both between signal topologies and between signal and SM background are negligible, the cross-section for any process $pp \to V q q$ with $V$ any SM boson and $q$ any SM quark can be obtained by comparing the $\hat{\sigma}$ cross-sections, rescaled with appropriate couplings, to the excluded cross-sections (minding the model-dependent relation between the couplings and $\Gamma_Q/M_Q$) and determining whether a specific scenario is excluded by the experimental search without the need of performing a dedicated recast (as it was done to construct Fig. 4). This is possible provided the results of the searches are presented in the $(M_Q, \Gamma_Q/M_Q)$ plane, as it has been done in the last section and in Refs. [12][43].

In Fig. 4 the $\hat{\sigma}$’s for the process $pp \to bWj$ mediated by a $T$ interacting exclusively through charged current are shown on the left panel while on the right panel we report a comparison between the limit obtained through a numerical recasting and the limit obtained by rescaling the $\hat{\sigma}$ values with the coupling needed to obtain the corresponding width of the $T$ in this benchmark scenario. The results are qualitatively very close and allow to identify with good accuracy the excluded region of this benchmark scenario.
Finally, we consider the role of interference between signal and background for the $pp \rightarrow bWj$ channel in the scenario with $T$ mixing with third SM quark generation and coupling only through charged current. Such assumptions allow us to study the scenario through the parameterisation of Eqs. (1) and (4). To perform the analysis, we start from the fact that, for any specific point, characterised by the mass and $\Gamma_Q/M_Q$ ratio of the VLQ, the total number of events is composed by different contributions:

$$S + B = L(\sigma(s\epsilon_s + \sigma^\text{int}_{SB,\text{irr}}\epsilon^\text{int}_{SB,\text{irr}})) + B_{\text{irr+red}} \equiv L\sigma_{\text{eff}} + B,$$

(6)

where $L$ is the integrated luminosity, $B_{\text{irr}}$ and $B_{\text{red}}$ are the number of events for the irreducible and reducible background terms respectively (which sum to the total number of background events $B$) and $\sigma_{\text{eff}} \equiv \sigma_{s,\text{eff}} + \sigma^\text{int}_{SB,\text{irr},\text{eff}}$ is the fiducial cross-section that is accessed by the experiment. The latter can be described by folding the experimental efficiencies of each contribution in the expression of $\tilde{\sigma}$ of Eqs. (1) and (4) as:

$$\sigma_{\text{eff}}(C_2, M_Q, \Gamma_Q; \chi_Q) = C_2^2 \tilde{\sigma}(M_Q, \Gamma_Q; \chi_Q) + C_2^2 \tilde{\sigma}^\text{int}_{SB,\text{irr}}(M_Q, \Gamma_Q, \chi_Q)\epsilon^\text{int}_{SB,\text{irr},\text{eff}}(M_Q, \Gamma_Q, \chi_Q)
$$

$$\equiv C_2^2 \tilde{\sigma}_{s,\text{eff}}(M_Q, \Gamma_Q) + C_2^2 \tilde{\sigma}^\text{int}_{SB,\text{irr},\text{eff}}(M_Q, \Gamma_Q, \chi_Q).$$

(7)

The $\tilde{\sigma}^\text{int}_{SB,\text{irr},\text{eff}}$ plots for the interference between signal and SM background are provided in Fig. 8. Notice the different behaviour in the case of dominantly LH or RH coupling chirality of the $T$ and that, as expected, the scenario with dominant LH chirality produces larger interference contributions as the $T$ mass approaches the top mass region.

In Fig. 9 the values of $\tilde{\sigma}_{s,\text{eff}}$ and $\tilde{\sigma}^\text{int}_{SB,\text{irr},\text{eff}}$ are provided for the signal and for the interference term in the case of dominant LH chirality, considering the signal region targeting final states with an electron in the CMS search [67]. With such information and with the knowledge of the total background $B$ (from experimental data), it is possible to reconstruct the number of events for $S + B$ for each point in the $(M_Q, \Gamma_Q/M_Q)$ plane through Eqs. (6) and (7).

The previous results for a $T$ decaying only through charged currents can be reinterpreted in terms of scenarios where other decay channels (which do not play a role as interference) are open, such as, e.g., $T \rightarrow St$ for a (generic) new BSM scalar $S$. This allows us to modify the value of the coupling while keeping the $\Gamma_Q/M_Q$ ratio fixed. As a practical example of the procedure described above, we consider the point with $M_T = 600$ GeV and $\Gamma_T/M_T = 10\%$. The values of $\sigma_{\text{eff}}$ and the relative contribution of the interference term are plotted as function of the $C_2 \equiv C_{T_{Wb}}$ coupling in Fig. 10, considering $C_{T_{Wb}}$ in a range for which $\sigma_{\text{eff}}$ is larger than $10^{-1}$ fb up to when the partial width becomes equivalent to 60 GeV, i.e., 10% of the mass. As it can also be inferred from

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5One should still check that the partial width $\Gamma(T \rightarrow W^+b)$ is still smaller than the total width.
Figure 8: \( \hat{\sigma}_{SB}^{int} \) values at 13 TeV (in pb) for the process \( pp \to bWj \) mediated by a \( T \) interacting with third generation SM quarks exclusively through charged current, for the interference between signal and SM background with dominant LH (RH) coupling chirality of the \( T \) in the left (right) panel.

Figure 9: \( \hat{\sigma}_{S,eff} \) and \( \hat{\sigma}_{SB,eff}^{int} \) values at 13 TeV (in pb) for the process \( pp \to bWj \) mediated by a \( T \) interacting with third generation SM quarks exclusively through charged current, for the pure signal (left panel) and for the interference between signal and SM background with dominant LH coupling chirality of the \( T \) (right panel). The signal region corresponding to the efficiencies is the single electron from the CMS search [67].

Eq. (7), the contribution of the interference term becomes more and more relevant as the \( C_2 \) coupling decreases, eventually becoming dominant with respect to the pure signal, but the fiducial cross-section \( \sigma_{eff} \) decreases as well. It is now straightforward to apply a CL analysis to determine the significance for exclusion or non-exclusion of the tested point. The reported numbers of background and observed events in the electron signal region by [67] are 95 ± 17 and 78 respectively with a luminosity of 2.3 fb\(^{-1}\), which imply that the quantity \( \sigma_{eff} \times L \simeq 30 \) is excluded at 95% CL, or that \( \sigma_{eff} \) has to be less than 13 fb. Such value places an upper bound on the \( T \) coupling \( C_{TWb} \lesssim 0.27 \), in a region for which the interference contribution to the signal is around -1.7%.

The relative importance of the interference contributions becomes larger as the luminosity increases. Rescaling the number of background events for the nominal highest luminosity for the LHC, 3 ab\(^{-1}\), we obtain \( B = 105556 \). With such value, and assuming a systematic uncertainty for the background of 5%, the maximum expected value of \( \sigma_{eff} \) for 95% CL exclusion is 3.6 fb, corresponding to \( C_{TWb} \lesssim 0.2 \), in a region for which the interference
\[ M_T = 600 \text{ GeV} \]
\[ \Gamma_T / M_T = 10\% \]

The contribution to the signal is around -3.4%.

We stress that this example represents an ideal situation in which the signal and interference contributions can be factorised in a simple and gauge-invariant way. More complex scenarios, in which the VLQ can couple through neutral currents and/or other BSM states, in such a way that other interference terms are non-negligible, cannot be reinterpreted analogously to the example of this section.

\section{Conclusions}

We have studied in a model-independent way processes of single production of VLQs with non-negligible width at the LHC, exploiting a simple, yet robust, framework for the presentation of experimental results and for their subsequent reinterpretation in terms of any scenario of new physics beyond the SM which predict VLQs of generic masses, couplings and total width which can decay into SM final states. Such framework can be generalised also for different BSM scenarios or for analyses of single VLQ production where QCD NLO effects are considered.

We have assessed the role of the total width in the determination of kinematic distributions of the final state finding that, in some cases, the shapes of such distributions can significantly be deformed depending on the \( \Gamma_Q / M_Q \) ratio. We have numerically recast a CMS search to determine how bounds in the plane \( (M_Q, \Gamma_Q / M_Q) \) change and, finally, we have compared the results of the numerical recasting in one of the considered scenarios to those from the model-independent procedure, obtaining an excellent agreement. Finally we have discussed the role of interference terms, usually neglected in experimental analysis, described issues related to the reinterpretation of results if such terms are not negligible and applied a procedure for reinterpretation in an ideal scenario in which such terms can be easily factorised.

The possibility to interpret observed data in terms of exclusion regions in the parameter space of models of new physics a is a crucial step for any phenomenological analysis of BSM scenarios. Nevertheless, in some cases, the experimental analysis techniques cannot be easily recast through phenomenological tools. In this case, for interpretations to be reliable, experimental results should provide all the essential information, so that a minimal, but complete, set of information can profitably be used for the characterisation of VLQs with generic assumptions on their mass, couplings and total width. In particular, the procedure adopted here allows for the possibility to perform a reinterpretation without the need of dedicated tools, thus growing the possibilities to test scenarios of new physics predicting VLQs.
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