Fully hadronic decays of a singly produced vector-like top partner at the LHC

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ABSTRACT: Single production of vector-like top partners is becoming a major focus of new searches, as the increasing mass limits on vector-like quarks obtained by the ATLAS and CMS collaborations are such that single production is becoming competitive with respect to pair production. Typically searches focus on decays containing leptons in the final state in order to have less background from the Standard Model processes. However the current centre of mass energies available in the latest LHC runs limit the searches to low masses. Fully hadronic final states may be an alternative option for discovery, as they allow a larger number of signal events if backgrounds can be kept under control. We study the fully hadronic decay of a singly produced vector-like top partner and we show a strategy to extract the signal over the background, considering as a benchmark the 20 fb$^{-1}$ of data collected at 8 TeV with the latest run of the LHC.

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1. Introduction

The discovery of the Higgs boson in 2012 allowed to establish the effective description of the fundamental laws of nature provided by the Standard Model of particle physics. The Large Hadron Collider (LHC) has also a strong potential for the discovery or exclusion of new particles, as expected in the different extensions of the Standard Model. Among these, many contain top partners (such as extra-dimensional models, little Higgs models, strong electroweak sector and composite Higgs models). These new multiplets are typically of vector-like type, therefore vector-like quarks [1] (VLQ) constitute a central piece of evidence for a set of models which summarise different possibilities of physics beyond the standard model. Many ATLAS [2–5] and CMS [6–11] searches have been recently performed in order to discover or set bounds on this type of particles related to the top sector. In many cases, as a simplifying assumption supported by theoretical expectations, only mixing to the third quark generation was considered. However partial mixing to the light generations should be allowed and is indeed a quite general expectation in the case of an extended CKM matrix (see [12] for a general parameterisation and suggestions of LHC signatures of this type; for a discussion mainly focussing instead on the scenario of dominant third generation coupling to the vector-like quarks see [13]; for a general discussion of mixing effects in the limit where the vector-like quarks are integrated out of the effective Lagrangian see [14]). Experimentally these studies are now being performed in view of their relevance for phenomenology and model building constraints [15], [16]. The crucial point is that even a small mixing to the first generation may have important phenomenological consequences as production would be driven by the first generation couplings due to the large light partonic content in the colliding protons at the LHC. In such a scenario, the couplings to the third generation and in particular the top quark, would be very relevant in the decay modes, as experimentally these decays give several clear signatures with respect to background processes from the standard model. In this work, we consider the electroweak
singly produced top partner (mainly through the flavour changing vertex $TZu$) and the decay of the $T$ into a top quark and a Higgs boson. Finally, we considered hadronic decays of both the top (three jets) and the Higgs boson (two jets); we therefore designed our analysis on events with 5 final jets as signature, plus an additional forward jet from the production. This choice of fully hadronic final states has some important advantages with respect to other choices for the decays of the Higgs and top: in the first instance, larger branching ratios lead to a higher number of events. As a second point, we shall show that a full mass reconstruction is achievable, something not possible in the corresponding leptonic signatures.

2. The model

From the theoretical side, our analysis is based on a general parameterisation [12] of models with vector–like quarks. All different configurations basically depend on the choice of a type of multiplet for the new quarks (singlet, doublet, triplet, etc.) and the assignment of the quantum numbers. This work is focused on a non-standard doublet containing a top partner $T$ of electric charge $2/3$ and an exotic $X$ quark of electric charge $5/3$. This doublet corresponds to a shift of one unit of hypercharge with respect to a standard doublet and it is much less constrained by flavour than other choices because it does not contain a bottom quark partner. For a detailed analysis of the phenomenological implications for such a multiplet see [17–19]. From a model building point of view, this multiplet is also interesting as it emerges in some strong sector extensions of the Standard Model [20–24]. For this multiplet a large coupling of the top partner to the first generation of quarks is phenomenologically allowed [18]. Note however that our particular choice is not restrictive apart from the detailed values of branching ratio in the final state we analyse. In fact, a generic heavy $T$ will decay to standard model quarks and $W$, $Z$, $H$ bosons. As typical minimal masses allowed by the present LHC searches are in the 500-700 GeV range [3,7,25,26] from pair production analyses, to a good approximation the decay rates are consistent with the asymptotic predictions of the equivalence theorem (in the ratio 2 : 1 : 1 for decays into $W$, $Z$, $H$ of a heavy top quark, but with different ratios if the quantum numbers are not the standard model ones). In the case of this non-standard doublet, the following decay modes are possible: $T \rightarrow Zu^i$, $Hu^i$ in the ratio 1 : 1, but depending on the selection of the couplings a given channel $i$ can be enhanced ($u^i$ means quarks of up type $i$). On the other hand, for the exotic partner $X \rightarrow W^+u^i$ only, due to its exotic electric charge.

The effective Lagrangian for a general formulation of VLQ in [12] can be restricted for $T$ and $X$ type of vector-like quarks in the non-standard doublet:

$$
\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_T}{\Gamma_T}} \frac{g}{2c_W} [T_R Z \gamma^\mu u^i_R] \right\} - \kappa_T \left\{ \sqrt{\frac{\zeta_T}{\Gamma_T}} \frac{M}{v} [T_L H u^i_R] \right\} + \sqrt{\frac{\zeta_T}{\Gamma_T}} \frac{m_t}{v} [T_R H t_L] \\
+ \kappa_X \left\{ \sqrt{\frac{\zeta_X}{\Gamma_X}} \frac{g}{\sqrt{2}} [X_R W^\mu u^i_R] \right\} + h.c.
$$

(2.1)

where we have neglected terms proportional to the light quark masses. The terms proportional to the top quark mass can be also neglected as they typically induce corrections
of the order of 10%-20% for $M = 600$ GeV (therefore of the order of incertitude in the present searches) except for the case of the coupling to the Higgs boson, which is therefore explicitly included. Apart from this chiral flipped term to the Higgs boson, all other terms have the same chirality. The Lagrangian terms with switched chirality ($L \leftrightarrow R$) are possible, but suppressed as explained above and detailed in [12]. The parameters $\kappa_T$, $\kappa_X$ are the coupling strengths and determine the strength of single production. The parameters $\zeta_i$ and $\xi_i$ are directly linked to the branching ratios ($\zeta_{jet}$ includes the contributions of the two light generations, which experimentally go both to jets): 

$$BR(T \rightarrow Zj) = \frac{\zeta_{jet} \xi_T^T}{1 + \zeta_3 \xi_T \delta_H}, \quad BR(T \rightarrow Zt) = \frac{(1 - \zeta_{jet}) \xi_Z^T}{1 + \zeta_3 \xi_Z \delta_H},$$

(2.2)

$$BR(T \rightarrow Hj) = \frac{\zeta_{jet}(1 - \xi_H^T)}{1 + \zeta_3 \xi_H \delta_H}, \quad BR(T \rightarrow Ht) = \frac{(1 - \zeta_{jet})(1 - \xi_T^T)(1 + \delta_H)}{1 + \zeta_3 \xi_T \delta_H},$$

$$BR(X \rightarrow W^+j) = \zeta_{jet}, \quad BR(X \rightarrow W^+t) = (1 - \zeta_{jet}).$$

(2.3)

The branching fractions of the top partner $T$ only depend on the two parameters $\zeta_{jet}$ and $\xi_T^T$, as $\delta_H$ is a calculable function of the heavy mass scale for the vector-like quarks $M$ [12]:

$$\delta_H \sim 5 \frac{m_t^2}{M^2},$$

(2.4)

where we kept the leading order in $1/M^2$. Note that in these formulae we kept the decay rates into $Z$ and $H$ arbitrary (parameterised by $\xi_Z^T m$ which is equal to $1/2$ for the non-standard doublet case). The X partner in the non-standard doublet has a branching which depends on a single parameter $\zeta_{jet}$. These approximate but quite robust results allow to describe easily the phenomenology of the non-standard doublet and its single production. For a top partner coming from other multiplets the situation is not much different in terms of decay modes, as only the extra decay to $W$ and quarks will be present, but those to $Z$, $H$ and quarks which we discuss in the following will be present and non negligible due to the equivalence principle being already a good approximation for vector-like masses $M$ of the order of 600 GeV or more. However constraints on different multiplet may be different and in some cases stronger (we indicated above flavour bounds, but also electroweak precision tests and low energy observables may give important bounds, see [17–19] for details).

3. Production

In this work we focus on the single production of $T$ in association with a light jet. If only mixing to the third generation were allowed, a single $T$ would be produced uniquely in association with a top quark via an s-channel $Z$ boson, thus leading to typically small cross sections. On the other hand, allowing a coupling to the up-quark, even if small, open the possibility for single production in association with a light jet via s- and t-channel $Z$ exchanges, which offer much larger production rates [12].

In order to study the production and hadronic decay of a singly produced heavy vector-like top, we have used standard Montecarlo simulation tools. The production of samples
was done with MadGraph 5 [27] version 1.5.11, for both signal and backgrounds. For the signal, the model was implemented using Feynrules [28, 29], using the model files in [30].

Finally, the hadronisation of the parton–level samples have been done with Pythia 6 [31].

Cross sections and expected number of events for signal and each background involved in the analysis, at 8 TeV for 20 fb$^{-1}$, are listed in Table 1.

For the QCD sample, all jets were produced with a $p_T > 30$ GeV and within a pseudorapidity of $|\eta| < 5$. All the other background samples were produced with jets with $p_T > 10$ GeV and no cut on the pseudorapidity. For all samples involving at least one Z, di–boson processes ZZ, WZ and Z+jets, the mass of the di–lepton pair was required to satisfy $M_{\ell\ell} > 50$ GeV, in order to avoid integration troubles. In hadronization step, the jets were built up with AK5 ($\Delta R = 0.5$) algorithm with the standard implementation provided by FastJet package [35].

The signal sample was produced with $p_T > 10$ GeV with the same packages. For the signal with $M_T = 734$ GeV around 700 events in full hadronic decay mode are expected at 8 TeV with 20 fb$^{-1}$. For this mass point the signal has a cross section around 200 fb. The choice of the $T$ mass value is taken in the range expected to be accessible to 8 TeV LHC analyses in order to show the interest of performing a more detailed and dedicated analysis within the LHC collaborations. It is clear that analyses to be performed at a higher centre of mass energy in the future, for example at 13 TeV for the LHC and seeking particles in the TeV range, will require different dedicated analyses, for example using boosted objects [32, 33]. The preliminary study we perform will not cover this case as typical efficiencies are not known for a 13 TeV case and analysis techniques will be probably different.

4. Analysis

The final state we are interested in contains 5 jets (3 b-jets, two of which coming from a Higgs decay, and 2 jets from the $W$ decay) which come from the $T$, plus a sixth, more forward jet from the production. The main issue with the analysis is to extract the signal over the large QCD background, as we aim to study a fully hadronic signal for the benefit of having a larger signal cross-section times branching ratios and full mass reconstruction.

| Process       | $\sigma_{8\text{TeV}}$ (pb) | Ex. Events     |
|---------------|-----------------------------|----------------|
| Signal ($T\bar{T}$) | 0.2                         | 700            |
| QCD (bbjjj)   | 500                         | 10,000,000     |
| W+jets        | 37,509                      | 750,180,000    |
| Z+jets        | 3,503.71                    | 70,074,200     |
| $t\bar{t}$    | 234                         | 4,680,000      |
| single-$t$    | 114.85                      | 2,297,000      |
| Di-boson      | 96.82                       | 1,936,400      |

Table 1: Cross sections and number of events for signal and backgrounds (after generation cuts). Branching ratio to full hadronic final state was taken into account for the signal.
All the different backgrounds with a similar signature were included in order to check their relevance in the analysis. Ordered by expected number of events, at 20 fb$^{-1}$, and the difficulty to differentiate them from the signal the backgrounds involved were QCD, W + jets, Z + jets, $t\bar{t}$, single top, and di-boson (WW, WZ, ZZ).

The fully hadronic channel allows the full mass reconstruction of the $T$. The analysis strategy will consist on reconstructing each decay products (top, Higgs) and then on looking for an accumulation of events around the $T$ mass while Standard Model background processes are expected to form a continuous distribution. Note also that this strategy is possible thanks to the relatively low mass range still allowed for the $T$, while for masses above the TeV (which will be accessible at the higher energy runof the LHC) the Higgs and W (top) are expected to be boosted and the jets from their decays merged.

First the jet association to reconstruct the decay products will be presented, then we will present the various criteria put in place in order to reduce background events. The jets association was performed after basic kinematical selection but before any cut on the invariant masses. The method used to identify the jets coming from the top partner is the following:

- Identify b-jets. (We only require at least two b’s.)
- For the Higgs decay, all pairs of b-jets passing the criteria $\Delta R_{jj} < 2.5$ are retained. If more than one pair is fulfilling the angular requirement, the pair with the closest mass to the Higgs mass (125 GeV) is chosen.
- From the remaining jets, all possible pairs are formed and the one with closest mass to W-mass (80 GeV) is identified as the W.
- Finally, from the remaining jets, the previously identified W-jets are coupled with a third jet. The top b-jet is selected as the jet which, combined with W ones, gives the invariant mass closest to the top mass (172 GeV).

Characteristics of the signal have been exploited in order to differentiate it from the backgrounds. The main characteristic is the presence of a Higgs boson, as a handle to reduce the backgrounds. In Table 2 the cut flow to extract the signal is shown together with the corresponding numbers of events expected for 20 fb$^{-1}$ in full hadronic decay mode. All cuts were applied one after the other in the order given in the following list:

- **Cut 0**: The first step consists in a preliminary event selection that mimics the case of a detector: an event is kept if it has at least 6 jets with $p_T > 30$ GeV, at least five jets within $|\eta| < 2.5$ and at least one jet within $2 < |\eta| < 5$. The five jets coming from the $T$ are more central, while the sixth jet produced in association with the single $T$ tends to be forward. In Figure 1 we show the pseudorapidity of the sixth jet at parton level.
- **Cut 1**: First kinematical selection: $p_T > 150$ GeV was required for the leading jet in each event, $p_T > 80$ GeV for the subleading one and $p_T > 60$ GeV for the 3$^{rd}$ and
Figure 1: $\eta$ of the light jet that is produced in association with the top partner at parton level.

$4^{th}$ leading jets. Figure 2 shows the distributions for the $p_T$ of the six leading jets for signal and backgrounds.

- **Cut 2**: The third cut involves the total hadronic energy ($H_T = \sum |p_T^j|$), which is plotted in Figure 3 for backgrounds and signal. The massive $T$ is decaying into top and Higgs particles, which are the two heaviest particles of the Standard Model. This should lead to higher hadronic energy than for QCD, $W + jets$ and $t\bar{t}$ events. Events with $H_T > 630$ GeV were selected.

- **Cut 3**: We required each event to have at least two b jets. A very loose b tagging selection (90% efficient) was considered.

- **Cut 4**: The jets coming from the Higgs boson have typically a $\Delta R_{jj} < 1.8$. The Higgs boson is produced boosted within the decay of $T$. This non-zero momentum implies that the decay products of the Higgs boson tend to be close together.

- **Cut 5**: The $p_T$ of the reconstructed Higgs and top quark for signal and backgrounds are shown in Figure 4, in a 2D histogram. It is interesting to notice that in the case of backgrounds the reconstructed Higgs and top have a smaller $p_T$ than the signal. Only events which have a Higgs with $p_T > 200$ and a top with $p_T > 300$ were selected.

- **Cut 6**: $\Delta R_{HW}$ is the $\Delta R$ between the reconstructed Higgs and $W$, which is plotted in Figure 5. Selecting only the events within $2.2 < \Delta R_{HW} < 3.5$ helps to reduce QCD and $W + jets$ background events.
Figure 2: $p_T$ of the six leading jets for backgrounds (stacked) and signal (over-imposed).
Figure 3: *Total hadronic energy for backgrounds (stacked) and signal (over-imposed).*

Figure 4: *Reconstructed Higgs $p_T$ in the x axis and reconstructed top $p_T$ in the y axis for backgrounds (left) and signal (right).*

- **Cut 7**: The $\Delta \phi_{jj}$ of the b jets identified as coming from the Higgs boson and the $\Delta \phi_{jW}$ between the reconstructed W and the jet which formed the top are expected
Figure 5: $\Delta R$ between the reconstructed Higgs and W for backgrounds (stacked) and signal (over-imposed).

...to be mainly central for the signal while more evenly distributed for backgrounds. The events that have $\Delta \phi_{jj} < 2.0$ and $\Delta \phi_{jW} < 3.3$ were selected. This cut is specially useful for reducing QCD and W+jets background events.

- **Cut 8**: The preliminary event selection required a minimum of jets inside and outside the acceptance. However, at this stage we noticed that a cut on the maximum number of jets can be useful to remove $t\bar{t}$ events. We therefore selected only events with strictly < 9 jets.

- **Cut 9**: The $\Delta \phi_{jj}$ between the jets of the W are also expected to be more centered around zero in the signal with respect to backgrounds. Only events with $\Delta \phi_{jj} < 2.3$ were kept. This cut was required to reduce single–top background.

- **Cut 10**: Finally, only events with a Higgs candidate with a mass between 100 GeV and 135 GeV were kept for the analysis.

- **Cut 11**: An additional observable can be constructed in order to differentiate the signal from $t\bar{t}$ background events. It is the relative total hadronic energy, and it is defined as the ratio between the $p_T$ of the decay products identified as the Higgs and top and the total hadronic energy of the event:

$$\frac{p_T^H + p_T^t}{H_T}.$$
Figure 6: Mass of the reconstructed Higgs for backgrounds (stacked) and signal (over-imposed).

All events with a relative total hadronic energy bigger than 0.65 were kept. The corresponding plot is shown in Figure 7.

- **Cut 12**: Finally, in order to further reduce the residual $t\bar{t}$ events, a geometrical observable was studied. The aplanarity measures how much the objects of an event are contained in a plane, and it varies from 0 for fully spherical events to 1 for planar events. Typically, events coming from our signal are more planar than some of the backgrounds. Events with aplanarity bigger or equal to 0.06 were therefore discarded.
| Cut  | Signal  | QCD  | W+jets  | Z+jets  | $t\bar{t}$ | $t$ | D-boson |
|------|---------|------|---------|---------|-----------|----|---------|
| 0    | 258     | 1233653 | 4763299 | 16102675 | 1152086 | 277373 | 90584   |
| 1    | 0.57 ± 0.02 | 0.05 ± (4 × 10⁻³) | 0.10 ± (4 × 10⁻³) | 0.14 ± (5 × 10⁻³) | 0.09 ± (2 × 10⁻³) | 0.07 ± (7 × 10⁻³) | 0.09 ± 0.01 |
| 2    | 0.84 ± 0.01 | 0.86 ± (7 × 10⁻³) | 0.22 ± 0.01 | 0.41 ± 0.01 | 0.83 ± 0.01 | 0.71 ± 0.06 | 0.40 ± 0.04 |
| 3    | 0.94 ± 0.01 | 0.69 ± 0.01 | 0.75 ± 0.06 | 0.82 ± 0.03 | 0.55 ± 0.01 | 0.83 ± 0.09 | 0.774 ± 0.09 |
| 4    | 0.91 ± 0.01 | 0.58 ± 0.02 | 0.56 ± 0.06 | 0.57 ± 0.02 | 0.54 ± 0.01 | 0.45 ± 0.07 | 0.55 ± 0.09 |
| 5    | 0.93 ± 0.01 | 0.61 ± 0.02 | 0.54 ± 0.08 | 0.62 ± 0.03 | 0.76 ± 0.01 | 0.56 ± 0.11 | 0.76 ± 0.15 |
| 6    | 0.74 ± 0.01 | 0.66 ± 0.02 | 0.66 ± 0.12 | 0.66 ± 0.05 | 0.71 ± 0.01 | 0.71 ± 0.16 | 0.70 ± 0.16 |
| 7    | 0.96 ± 0.01 | 0.94 ± 0.03 | 0.89 ± 0.18 | 0.90 ± 0.07 | 0.85 ± 0.03 | 0.67 ± 0.17 | 0.93 ± 0.24 |
| 8    | 0.90 ± 0.02 | 0.79 ± 0.05 | 0.78 ± 0.17 | 0.86 ± 0.07 | 0.87 ± 0.03 | 0.98 ± 0.26 | 0.86 ± 0.23 |
| 9    | 0.89 ± 0.02 | 0.30 ± 0.05 | 0.37 ± 0.11 | 0.26 ± 0.03 | 0.47 ± 0.04 | 0.88 ± 0.29 | 0.25 ± 0.11 |
| 10   | 0.89 ± 0.02 | 0.62 ± 0.03 | 0.58 ± 0.26 | 0.56 ± 0.11 | 0.55 ± 0.05 | 0.49 ± 0.20 | 0.53 ± 0.35 |
| 11   | 0.88 ± 0.02 | 0.79 ± 0.08 | 0.93 ± 0.49 | 0.73 ± 0.17 | 0.73 ± 0.03 | 0.74 ± 0.36 | 0.71 ± 0.56 |
| 12   | 0.88 ± 0.02 | 0.79 ± 0.12 | 0.93 ± 0.49 | 0.73 ± 0.19 | 0.73 ± 0.05 | 0.75 ± 0.39 | 0.71 ± 0.64 |
| combined | 0.15 ± 0.04 | (6 ± 5) × 10⁻⁴ | (7 ± 9) × 10⁻⁴ | (10 ± 8) × 10⁻⁴ | (1 ± 0.6) × 10⁻³ | (1 ± 2) × 10⁻³ | (0.4 ± 2) × 10⁻³ |

**Table 2:** Number of events for signal and backgrounds after the first cut, and efficiencies of each stage of the cutting procedure.
Figure 7: Relative total hadronic energy for backgrounds (stacked) and signal (over-imposed).

In Table 2, we show the efficiency of each cut in the procedure described above: the first line contains the number of events after the initial Cut 0, while on the following lines the efficiencies of the cuts for signal and background samples are shown after each of the 12 cuts. The last line of the table contains combined efficiency of all the cuts on each sample of events. As this analysis was done at the hadronic level (after showering), more jets were expected in comparison to parton level due to radiation and jet reconstruction algorithm.

In Figure 8 the peak reconstruction is shown, with the aforementioned identification procedure and after all the cuts. In this figure a clear peak around 730 GeV is observed with the signal clearly visible over the ensemble of backgrounds. The lack of softness of the distribution is due to the lack of statistics in the MonteCarlo samples for the backgrounds, specially for W+jets. After all cuts, we selected the number of events falling into a window of 20 GeV around the $T$ mass, i.e. within $710 < M_{jjjj} < 750$ GeV. We therefore obtain an enhanced signal over background ratio, with:

$$\frac{S}{\sqrt{S + B}} = 3.04 \pm 0.04, \quad \text{and} \quad \frac{S}{B} = 0.12 \pm 0.02.$$  \hspace{1cm} (4.1)

The analysis strategy based simulation was performed with a physical width of the $T$ particle preset to 1 GeV in the FeynRules implementation. The couplings we used, however, give a width of 11 GeV. Changing the physical width does not affect any of the selection criteria, but simply affects the final selection based on the invariant mass of the 5 jets. We checked that, with a width of 11 GeV, an opening up to 30 GeV as mass window is necessary to include around 2 sigma of the signal. The $S/\sqrt{S + B}$ is then changing from
3.04±0.04 to 3.10±0.04, thus still compatible within the errors. We can therefore conclude that the physical width of the $T$ does not affect significantly this search.

![Figure 8: Reconstructed $T$ mass after all cuts for backgrounds and signal (stacked).](image)

This full study was done with the help of MadAnalysis5 package [34].

5. Conclusions

We have performed a simplified analysis for single production of a vector-like top partner $T$ in association with a light jet, with the $T$ decaying into a top quark and a Higgs boson in the fully hadronic channel. We thus demonstrated a strategy to extract the signal over the background, considering as a benchmark the 20 fb$^{-1}$ of data at 8 TeV collected within the latest run of the LHC and a benchmark mass around 730 GeV, which is within the range of reach for these analyses. This study suggests the interest in performing a dedicated analysis by the LHC experimental collaborations. Indeed the larger branchings in the hadronic decays give a higher number of signal events and full mass reconstruction is achievable, something which is not possible in the corresponding leptonic signatures studied at present.

This study also shows the importance of even small mixings of the $T$ to the first generation as production is driven by these first generation couplings due to the large light partonic content in the colliding protons. The couplings to the third generation and in particular to the top quark, allow decay modes which give clear signatures with respect to background processes from the standard model.
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