Search for single production of a top quark partner
via the $T \to th$ and $h \to WW^*$ channels at the LHC

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Abstract

Many scenarios of physics beyond the Standard Model that address the hierarchy problem also predict the existence of vector-like top quark partners, which are generally expected around the TeV scale. In this paper, we propose to search for a vector-like top quark partner with charge $2/3$ in a simplified model including only two free parameters, the coupling constant $g^*$ and top quark partner mass $m_T$. We investigate the observability of the top quark partner through the process $pp \to T(\to th)j \to t(\to bW^+ \to b\ell^+\nu_\ell)h(\to WW^* \to \ell^+\nu\ell^-\bar{\nu}_j)$, where $T$ is the heavy top quark partner and $h$ the SM-like Higgs boson, at the Large Hadron Collider (LHC). The discovery prospects and exclusion limits on the parameter plane defined by $(m_T, g^*)$ are obtained for the already scheduled LHC runs as well as at the future High-Luminosity LHC (HL-LHC). The constraints and projected sensitivities are also interpreted in a realistic model, i.e., the minimal Composite Higgs Model with singlet top quark partners. We finally also analyze the projected sensitivity in terms of the production cross section times branching fraction at the (HL-)LHC.

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I. INTRODUCTION

To solve the gauge hierarchy problem, many extensions of the Standard Model (SM) predict top quark partners, which play an important role in cancelling potentially large top quark loop corrections to the Higgs boson mass (for a review, see [1]). Vector-like top quark partners $T$’s with the same color and Electro-Weak (EW) quantum numbers as the top quark ones have been introduced in many New Physics (NP) scenarios, such as little Higgs models [2], extra dimensions [3], twin Higgs models [4] and Composite Higgs Models (CHMs) [5]. In general, these new particles are at or just below the TeV scale and might generate characteristic signatures at current and future high energy colliders. In particular, the discovery of these top quark partners at the Large Hadron Collider (LHC) will be very important to test these NP models.

At the LHC, vector-like top quark partners can be produced in pairs or singly, both of which have been widely studied via various final states in the literature: see, e.g., [6–18]. While for light $T$ states their pair production is vastly dominant, for heavy top quark partners, the single channel mode eventually dominates over pair production due to a larger phase space. Vector-like top quark partners generally only mix with the third generation SM quarks [19], but, in some models, they can mix with the light SM quarks generations too, which opens up new production mechanisms and makes the investigation of such new particles at the LHC very promising [20–24]. Given the current constrains from direct searches by the ATLAS and CMS Collaborations with an integrated luminosity of $35–36 \text{ fb}^{-1}$, the minimum mass of a top quark partner is set at about $1.2–1.3 \text{ TeV}$, for a variety of signatures [25]. Very recently, the ATLAS Collaboration presented a search optimized for a singly produced vector-like $T$ quark at $\sqrt{s} = 13 \text{ TeV}$, subsequently decaying via $T \rightarrow bW$ with the $W$ boson decaying leptonically [26]. For the $T$ quark mass range of $800 \text{ GeV}$ to $1200 \text{ GeV}$, the upper exclusion limit on the $TWb$ coupling strength $C_{Wb}^L$ is $0.25–0.49$. However, such bounds can in principle be lowered when the top quark partners mix with lighter SM quark generations [21, 22] or exotic decay modes exist [27].

The High-Luminosity LHC (HL-LHC) is expected to reach $3000 \text{ fb}^{-1}$ [28], which will be very beneficial for discovering possible new physical signals even for small production and/or decay rates. Hence, at such a high luminosity, a variety of $T$ decay channels can in principle be accessed. In the past few years, the discovery of a SM-like Higgs boson $h$ [29] has rendered the $T \rightarrow th$ decay channel promising, so that it has been considered as a $T$ search mode, wherein
the SM-like Higgs boson decays to $h \rightarrow b\bar{b}$ [30–32], $h \rightarrow \gamma\gamma$ [33] and $h \rightarrow ZZ$ [34]. As we know, the $h \rightarrow WW^*$ decay channel has the second largest Branching Ratio (BR), of about 22%, and also has the advantage of a smaller backgrounds than $h \rightarrow b\bar{b}$ (which is indeed the dominant mode). This encourages us to further analyze the $T \rightarrow th$ decay channel followed by the pure leptonic mode $h \rightarrow WW^* \rightarrow e^+\nu e^-\bar{\nu}$ in order to eventually provide a sensitivity comparable to that of other modes for the (HL-)LHC. Assuming single-$T$ production, for the hadronic and leptonic decay of the top quark, there are two cases for the final state, namely, two leptons plus multi-jets and trilepton signals, but the former will suffer from the large SM background coming from the $t\bar{t} +$ jets process. Therefore, we study here the observability of single-$T$ production at the (HL-)LHC via the $T \rightarrow t(\rightarrow bW^+ \rightarrow b\ell^+\nu_\ell)h(\rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu})$ decay channel, accompanied by at least one jet, $j$. (It should be noted that our results are model-independent and can be applied to several NP scenarios, including those with singlet top quark partners.)

This paper is organized as follows. In Sec. II we systematically analyze the signals and backgrounds for the single top quark partner production process in a simplified model, which only comprises two independent parameters, as well as present our strategy to determine the reconstructed masses for the Higgs boson and top quark partner, including discussing the exclusion and discovery potential at the (HL-)LHC. Finally, we present our conclusions in Sec. III.

II. SEARCHES FOR TOP PARTNERS AT THE HL-LHC

A. A simplified model including a singlet top quark partner

As proposed in Ref. [21], vector-like top quark partners could be embedded in different representations of the weak $SU(2)$ group. We here consider an $SU(2)$ singlet vector-like $T$ quark with charge 2/3. In many cases, such vector-like top quark partners share similar final state topologies with different BRs and single production couplings. Thus it is favourable to use simplified model approaches in searching for the possible signals of top quark partners at the LHC, which only include the mass of the top quark partner and its single production coupling as free parameters. A generic parametrization of an effective Lagrangian for top quark partners
is given by
\[ \mathcal{L}_{\text{eff}} = g^* \frac{g}{\sqrt{2}} \bar{T}_L W^\mu W_{\mu} + \frac{g}{2 \cos \theta_W} \bar{T}_L Z \mu \gamma^\mu t_L - \frac{m_W}{v} \bar{T}_R h t_L - \frac{m_t}{v} \bar{T}_L h t_R + h.c., \]
(1)
where \( g \) is the SM \( SU(2) \) gauge coupling constant and \( \theta_W \) is the Weinberg angle.

From Eq. (1), one can see that there are indeed only two free parameters, the top quark partner mass, \( m_T \), and the coupling strength to SM quarks in units of the SM coupling \( g, g^* \). In Fig. 1, we show the BRs of three decay channels \( T \rightarrow bW, tZ \) and \( th \) as well as their decay widths by varying the top quark partner mass at fixed \( g^* \). One can see that \( \text{BR}(T \rightarrow th) \approx \frac{1}{2} \text{BR}(T \rightarrow Wb) \) is a good approximation as expected from the Goldstone boson equivalence theorem [35]. Further, the width of the top quark partner is very small with respect to its mass. Thus, it is possible to factorize the production and decay parts of the scattering amplitudes and write the cross section as \( \sigma_T \times \text{BR}(T \rightarrow XY) \) for a generic channel, where \( \sigma_T \) is the single-\( T \) production cross section and \( \text{BR}(T \rightarrow XY) \) the decay rate into the generic \( XY \) final state.

B. Event generation and cut flow

In this subsection, we analyze the LHC observation potential by performing a Monte Carlo (MC) simulation of the signal plus background events and explore the sensitivity to the top
quark partner at the (HL-)LHC through the process:

\[ pp \rightarrow T(\rightarrow th)j \rightarrow t(\rightarrow bW \rightarrow b\ell^+\nu_\ell)h(\rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu})j. \]  

The Feynman diagram of the production and decay chain is presented in Fig. 2. The QCD

![Feynman diagram](image)

FIG. 2. The Feynman diagram for the production of a single $T$ quark (and a jet) including the decay chain $T \rightarrow t(\rightarrow b\ell^+\nu_\ell)h(\rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu})$.

Next-to-Leading Order (NLO) production cross section of the process $pp \rightarrow Tj$ is calculated in Ref. [36]. We here take from there a $K$-factor of 1.2 for the signal before event generation (i.e., inclusively). In the remainder, we will adopt three benchmark values for the $T$ mass, ie, $m_T = 1.0$, 1.2 and 1.5 TeV (which we will refer to in the legends as $T_{1000}$, $T_{1200}$ and $T_{1500}$, respectively).

All signal and background events are simulated at the LO by using MadGraph5-aMC@NLO [37] with the NN23LO1 Parton Distribution Function (PDF) set [38], with default renormalization and factorization scales. The parton shower and the fast detector simulations are done by PYTHIA 8 [39] and DELPHES 3 [40], respectively. At last, event reconstruction is performed with MadAnalysis5 [41], where the anti-$k_t$ algorithm [42] is used with a radius parameter $R = 0.4$ in order to select jets. Finally, we use $\sqrt{s} = 14$ TeV in all our plots as LHC energy.

For the leptonic decay of the top quark and the full leptonic Higgs decay mode, the typical signal is three charged leptons $\ell(=e,\mu)$, one $b$-jet, one forward jet and missing transverse
energy, \( E_T \). The backgrounds that can give three leptons in the final states which are considered in this analysis are: \( t\bar{t}V \) \((V = W, Z)\), \( t\bar{t}h \) and \( WZjj \). The \( t\bar{t} + \text{jets} \) process, which has large cross section, may also contribute to the background if the third lepton comes from a \( B \)-hadron semi-leptonic decay inside a \( b \)-jet. We do not consider other backgrounds from \( t\bar{t}t\bar{t} \), tri-boson events and \( thj \), though, because their cross sections are negligible after applying our selection cuts (see below). Further, we do not consider jets faking electrons either, because it is not supported in DELPHES, yet, we could estimate the emerging rate as being negligible, given the predominantly leptonic nature of the final state considered. Like for the signals, the cross sections of these backgrounds at LO are adjusted to NLO by means of \( K \)-factors, which are about 1.3 for \( t\bar{t}V \) \((V = W^\pm, Z)\) [43], 1.24 for \( t\bar{t}h \) [44] and 0.86 for \( WZjj \) [45]. The dominant top pair production cross section is normalized to the Next-to-NLO (NNLO) (in QCD) [46].

In our MC simulation, the following acceptance cuts are enforced for all signal and background events.

- **Basic cuts:** \( p_T(\ell) > 10 \text{ GeV}, p_T(j, b) > 15 \text{ GeV}, |\eta_{\ell,b}| < 2.5, |\eta_j| < 5, \Delta R_{bj,b\ell,\ell j} > 0.4 \).

In order to choose appropriate selection cuts, in Fig. 3, we show some key normalized distributions for the signals and backgrounds, such as (some of) the transverse momenta \( p_T(\ell_i) \) and cone separations \( \Delta R(\ell_i, \ell_j) \), for all \( i \neq j = 1, 2, 3 \) leptons ordered in decreasing energy. Based on these kinematical distributions, we impose the following selection cuts.

- **Cut-1:** Exactly three isolated leptons \((N(\ell) = 3)\), with \( p_T(\ell_1) > 100 \text{ GeV} \) and \( p_T(\ell_2) > 25 \text{ GeV} \), at least two jets and one of these is an isolated \( b \)-jet \((N(b) = 1)\). Since the (most energetic) first lepton, \( \ell_1 \), is assumed to originate from the leptonically decaying top quark, we require \( \Delta R(\ell_1, \ell_2) > 2.5 \) and \( \Delta R(\ell_2, \ell_3) < 1 \).

The extra jet (from a valence quark emission) entering the signal final state always has a strong forward/backward nature, which is a useful handle in suppressing the SM backgrounds. The distribution of the pseudorapidity of the forward/backward jet is plotted in Fig. 4 for the signals and backgrounds. Based on this spectrum, one can further reduce the backgrounds through the following cut.

- **Cut-2:** The light untagged jet is required to have \(|\eta_j| > 2.4\).

The invariant mass of the \( b\ell_1 \) and \( \ell_2\ell_3 \) systems is plotted in Fig. 5 for the signals and backgrounds. One can see that, for \( T \) events, the invariant mass of the \( b \)-jet and the leading lepton,
FIG. 3. Normalized distributions in transverse momentum and cone separation for the signals and backgrounds.

$M_{b\ell_1}$, is always less than the top quark mass since the tagged $b$-jet and leading lepton in our signals come from the same top quark decay. A similar feature also appears for the invariant mass of the $\ell_2\ell_3$ system, which is very different from the resonant $Z$ boson one typical of most SM noise. Thus we can further reduce the backgrounds via the following cuts.

- **Cut-3**: $M_{b\ell_1} < 150 \text{ GeV}$.
- **Cut-4**: $13 \text{ GeV} < M_{\ell_2\ell_3} < 60 \text{ GeV}$.

To reconstruct the top quark partner mass, we use a cluster transverse mass, defined as [47]

$$M_T^2(b\ell_1\ell_2\ell_3) = (\sqrt{p_T^2(b\ell_1\ell_2\ell_3) + M_{b\ell_1\ell_2\ell_3}^2} + E_T)^2 - (\vec{p}_T(b\ell_1\ell_2\ell_3) + E_T)^2,$$

where $\vec{p}_T(b\ell_1\ell_2\ell_3)$ is the total transverse momentum of all visible particles (but the forward/backward jet) and $M_{b\ell_1\ell_2\ell_3}$ is their invariant mass. In Fig. 6, we show the transverse...
FIG. 4. Normalized distribution in pseudorapidity of the forward/backward jet for the signals and backgrounds.

FIG. 5. Normalized distributions in invariant mass of the $b\ell_1$ and $\ell_2\ell_3$ systems for the signals and backgrounds.

mass distribution $M_T(b\ell_1\ell_2\ell_3\not{E_T})$. From this figure, we can see that the transverse mass distribution has an end point around the top quark partner mass in the signal, unlike the backgrounds, which can then be used in the following cut to further remove SM noise.

- **Cut-5:** $M_T(b\ell_1\ell_2\ell_3\not{E_T}) > 600 \text{ GeV}$. 

FIG. 6. Normalized distribution in cluster transverse mass of the $b\ell_1\ell_2\ell_3\not E_T$ system for the signals and backgrounds.

TABLE I. The cut flow of the cross sections (in $10^{-3}$ fb) for our signals and the relevant backgrounds at the LHC with $\sqrt{s} = 14$ TeV. Here we take the gauge parameter as $g^* = 0.2$.

| Cuts      | Signals       | Backgrounds  |
|-----------|---------------|--------------|
|           | 1.0 TeV | 1.2 TeV | 1.5 TeV | $t\bar{t} + X$ | $t\bar{t} V$ | $t\bar{t} h$ | $WZjj$ | $Whjj$ |
| Basic cuts | 24     | 11      | 3.5     | $1.6 \times 10^7$ | 8400    | 240       | $5.1 \times 10^4$ | 98      |
| Cut-1     | 3.3    | 1.5     | 0.5     | 24     | 16.2   | 0.3       | 10      | 0.08    |
| Cut-2     | 1.9    | 0.84    | 0.28    | 4.1    | 0.55   | 0.01      | 10      | 0.007   |
| Cut-3     | 1.7    | 0.73    | 0.25    | 1.1    | 0.36   | 0.009     | 0.15    | 0.007   |
| Cut-4     | 1.4    | 0.6     | 0.21    | 0.51   | 0.15   | 0.005     | 0.024   | 0.002   |
| Cut-5     | 1.3    | 0.58    | 0.2     | 0.05   | 0.018  | $7.4 \times 10^{-4}$ | $9.7 \times 10^{-4}$ | $1.1 \times 10^{-4}$ |

In Tab. I, we show the cut flow of the signal and background cross sections after each selection for $g^* = 0.2$ and our three benchmark top quark partner masses. One can see that the backgrounds are suppressed very efficiently after imposing all listed cuts.
C. Analysis and results

As there are only a few events for both signals and backgrounds after the kinematics cuts, assuming any (HL-)LHC luminosity, we estimate the Discovery ($D$) prospects and Exclusion ($E$) limits using the formulae [48]

$$Z_D = \sqrt{2 \times L_{\text{int}} \left[ (\sigma_S + \sigma_B) \ln(1 + \frac{\sigma_S}{\sigma_B}) - \sigma_S \right]},$$  \hspace{1cm} (4)

$$Z_E = \sqrt{-2 \times L_{\text{int}} \left[ \sigma_B \ln(1 + \frac{\sigma_S}{\sigma_B}) - \sigma_S \right]},$$  \hspace{1cm} (5)

where $\sigma_S$ and $\sigma_B$ are the cross sections of each signal ($S$) and total background ($B$) after all cuts and $L_{\text{int}}$ is the integrated luminosity. Clearly, the values of $Z_{D,E}$ are dependent on the coupling parameter $g^*$ and the top quark partner mass.

![Graph](image)

FIG. 7. The discovery prospects (at 5$\sigma$) and exclusion limit (at 95% CL) for the signal on the ($m_T, g^*$) plane at the (HL-)LHC with 300 fb$^{-1}$ and 3 ab$^{-1}$, respectively.

At the HL-LHC, the integrated luminosity is planned to reach 3 ab$^{-1}$, a tenfold increase with respect to the standard LHC. Using Eqs. (4)–(5), we can obtain the expected sensitivity over the place ($m_T, g^*$) in terms of the discovery prospects and exclusion limit of our proposed
signals, as shown in Fig. 7, as function of the top quark partner mass, for these two \( L \) values. From this figure we can see that, at the HL-LHC, for \( m_T = 1.0 \) (1.2) TeV, the 5\( \sigma \) level (i.e., \( Z_E \geq 5 \)) discovery sensitivity on \( g^* \) would be about 0.24 (0.35), while the upper exclusion limit on \( g^* \) would be 0.16 (0.24) at 95\% Confidence Level (CL) or equivalently with \( Z_E \geq 2 \). For full luminosity at the standard LHC, \( g^* \) values probed are clearly \( \sqrt{10} \) higher. For illustration, the current exclusion limit obtained by the ATLAS Collaboration is 0.29 (0.49) for a singlet \( T \) quark of mass of 1.0 (1.2) TeV, using all other available \( h \) decay channels.

Certainly, our results can be applied to other NP models with such top quark partners, such as the minimal CHM of Ref. [17] with singlet top quark partners, where the coset structure is \( SO(5)/SO(4) \). The vector-like top quark partners can be either in the fourplet or singlet of the unbroken \( SO(4) \). In the singlet case, only one \( SU(2) \)-singlet charged \( 2/3 \) top quark partner is introduced. From the couplings of the top quark partner with the \( W \) boson and a \( b \)-quark, the mixing parameter \( g^* \) is given by

\[
g^* \simeq \frac{\sqrt{2} y m_W}{g m_T}, \tag{6}\]

where \( y \) is a Yukawa coupling controlling the mixing between the composite and elementary states. For illustration, with \( y = 1 \) and \( m_T = 1 \) TeV, one obtains \( g^* \simeq 0.17 \).

Because our results are obtained from fixed BRs in a simplified model, while the latter for different decay channels can be altered in other models, in Fig. 8, we plot the HL-LHC projected sensitivity in terms of the production cross section times BR (\( \sigma_T \times \text{BR}(T \rightarrow th) \)) as a function of the vector-like top quark partner mass. We find that single-\( T \) production and decay rates such that \( \sigma_T \times \text{BR}(T \rightarrow th) \sim 80 - 160 \) fb could be discovered at the HL-LHC for \( m_T \in [1.0, 1.6] \) TeV, while the cross sections \( \sim 37 - 74 \) fb will be excluded. These bounds are therefore more constraining than our results because of the different cut analysis (e.g., they look for an hadronic top decay) and a relative larger event rate.
FIG. 8. The excluded and observed cross section times BR rates for the single-$T$ signal as a function of the vector-like top quark partner mass $m_T$ at the HL-LHC.

...in the $h \to b \bar{b}$ channel, yet our analysis of the $h \to WW^*$ mode can represent a complementary candidate to search for a possible singlet top quark partner, at both the standard and HL-LHC.

III. CONCLUSION

New heavy vector-like top quark partners $T$ are predicted in many different NP models, which might then generate a rich phenomenology at the LHC. In this paper, we have studied the prospects of observing single-$T$ production at the current LHC and future HL-LHC via the $T \to th$ decay channel, followed by a leptonic top decay and $h \to WW^* \to \ell^+\ell^- + E_T$. We performed a model-independent analysis of this process at $\sqrt{s} = 14$ TeV with a simplified model which only includes two free parameters, the top quark partner mass $m_T$ and the EW coupling constant $g^*$. The discovery prospects at 5σ and exclusion limits at 95% CL in the parameter plane of the two variables $m_T$ and $g^*$ were obtained with both a standard and high luminosity, 300 fb$^{-1}$ and 3 ab$^{-1}$, respectively. For $m_T = 1.0$ (1.2) TeV, our best results (at the HL-LHC) show that the 5σ level discovery sensitivities of the coupling parameter $g^*$ are about 0.24 (0.36), while the exclusion limit at 95% CL on $g^*$ are given as $g^* \leq 0.16$ (0.24).
Our results can also be mapped over other NP models where the top quark partners only have couplings to the third generation of SM quarks, e.g., the minimal CHM with singlet top quark partners. In this scenario, we presented the projected sensitivity in terms of the production cross section times BR rates for the $T \rightarrow th$ channel. For $m_T \in [1.0, 1.6]$ TeV, rates of $\sigma \times BR(T \rightarrow th) ~ 80 – 160$ fb could be discovered while the cross sections $\sim 37 – 74$ fb would be excluded at the HL-LHC.

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