Reconstructing singly produced top partners in decays to Wb

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Fermionic top partners are a feature of many models of physics beyond the Standard Model. We propose a search strategy for single production of top partners focussing specifically on the dominant decay to Wb. The enormous background can be reduced by requiring a forward jet and exploiting jet substructure to suppress top-pair production. This simple strategy is shown to produce a sensitive search for single top-partner production, in the context of composite Higgs models, that has competitive mass reach with existing experimental searches for top-partner-pair production at the 8 TeV LHC.

CONTEXT AND INTRODUCTORY REMARKS

With the observation of a Standard Model-like Higgs boson [1,2] at the Large Hadron Collider (LHC), our understanding of electroweak symmetry breaking has been significantly enhanced. The attention of experiments at the LHC now turns to establishing the properties of this new resonance. The possibility that the resonance is actually a composite bound state remains open, and in this work we study a top partner search in the context of composite Higgs scenarios [3–8]. The discovery of such top partners would spectacularly elucidate the mechanism by which the scalar resonance mass is stabilised at the electroweak scale.

Although the Higgs boson can be a generic composite bound state, we focus on the realisation of the Higgs boson as a pseudo Nambu-Goldstone boson (pNGB) of the coset $G/H$, $G$ is an approximate global symmetry and $H$ is an unbroken subgroup. We assume partial compositeness [3] to evade flavour physics constraints [9]. Here, the Standard Model (SM) fermions obtain masses via mixing with composite bound states from the strongly coupled sector. Since SM fermions arise as admixtures of the elementary and the corresponding composite bound states, there are necessarily accompanying heavy excitations with the same SM quantum numbers, so-called top partners. They belong to a representation of the unbroken subgroup $H$.

Following Ref. [10] we adopt a minimal setup for $G = SO(5) \times U(1)_X$ and $H = SO(4) \times U(1)_X$. We assume $t_R$ to be a completely composite chiral state and only $q_L = (h, t)_L$ to be partially composite. In this short article we focus on evaluating the LHC’s sensitivity in discovering or excluding a top partner belonging to the singlet $\Psi = 1_{2/3}$ of the unbroken $SO(4)$. The operators $O$ induced by the interactions of the fermions in the strong sector are assumed to transform in the representation $r_O = 5_{2/3}$.

The interaction Lagrangian for $\tilde{T}$ is given by

$$\mathcal{L} = \mathcal{L}_{\text{kin}} - M_{\Psi} \bar{\Psi}\Psi + \left[ yf(\bar{Q}_L^i)^4U_{15}\Psi + yc_5(\bar{Q}_L^5)^4U_{15}t_R + \text{h.c.}\right]$$

and the mass eigenvalue of the top partner $\tilde{T}$ is approximately given by

$$m_{\tilde{T}} \approx M_{\Psi} \left[ 1 + \frac{y^2}{4g_{\Psi}^2}v^2 \right]$$

where $v = 246$ GeV and $g_{\Psi} = M_{\Psi}/f$.

As a result the phenomenology of $\tilde{T}$ is determined by four parameters: $(M_{\Psi}, y, c, f)$. $M_{\Psi}$ is the mass of the top partner, $y$ controls the mixing between the composite and elementary states, $c$ is an $O(1)$ parameter associated with the interactions of $t_R$ and $f$ is the symmetry breaking scale of the strong sector. By requiring the four parameters to conspire to give the observed top quark mass degree of freedom in this parameter space can be removed, i.e. we choose $y = 1$. In the following quantitative analysis we also choose $\xi = \frac{y^2}{f^2} = 0.2$ to ensure compatibility with electroweak precision tests [11–13].

Pair production of fermionic top partners has been thoroughly searched for at the LHC [14,15]. Top partners with masses less than 687 – 782 GeV are excluded depending on the branching ratio to different final states. In this work, we focus instead on single production: $pp \rightarrow q\tilde{T}b$. The cross section for single production is smaller than that for pair production at low masses of the top partner. However, depending on the weak coupling to the top partner, single production can begin to have a larger cross section in the mass-range of 600–1000 GeV [16]. Thus, well-designed searches for single

*Our results can be interpreted straightforwardly if the operators $O$ of the strong-sector fermions transform in the representation $r_O = 14_{2/3}$. 
production can potentially extend the mass-reach of the LHC experiments.

Singlet top partners decay to $Wb, tZ$ or $tH$ in the approximate ratio 2:1:1 respectively, and the significant branching fractions to $tZ$ and $tH$ have attracted previous attention\cite{10, 17, 18}. In particular, multi-leptonic final states arising from these decays make for searches with low background, albeit at a relatively low overall signal efficiency. Here, we have chosen to focus on the most abundant expected decay: $T \rightarrow Wb$, with subsequent decay of the $W$ boson to leptons. Trading a clean final state against a bigger background can be beneficial for large top partner masses \cite{30}. The present experimental limits are weakest for large values of the $T \rightarrow Wb$ branching ratio \cite{15}. We demonstrate that, by requiring a forward jet and exploiting jet substructure to suppress backgrounds from top-quark production, this relatively neglected channel can become a promising one for discovery of single top-partner production at the LHC.

ELEMENTS OF THE ANALYSIS

Samples

Signal events were simulated using MadGraph5 \cite{19} interfaced with PYTHIA 8.185 \cite{20} for parton-shower and fragmentation. Background samples of $t \bar{t}$ and $W+\text{jets}$ were generated with up to two and four additional partons using SHERPA \cite{21} 2.1.0. Single top quark production in the $t$-channel was modelled, in a four-flavor scheme \cite{22}, using POWHEG-BOX \cite{23} showered with PYTHIA 8.185.

Event selection and top-partner reconstruction

Analysis of the samples of simulated events is performed on the stable final-state particles using Rivet 2.1.1 \cite{24}. The event selection was designed to select singly produced $T$ quarks with subsequent $T \rightarrow bW$ decay. For leptonically decaying $W$-bosons, the signal event topology is characterised by a charged lepton, missing transverse momentum, an high-$p_T$ $b$-tagged central jet and a forward jet.

Final-state electrons are corrected for energy loss due to photon emission by combining them with all final-state photons within $\Delta R(e, \gamma) < 0.1$, where $\Delta R(e, \gamma)$ is the distance in the $\eta-\phi$ plane between the electron and the photon. Charged leptons are required to be isolated from other particles\footnote{Isolation criteria that were similar to those used in an ATLAS same-sign dilepton search \cite{25} were adopted. For electrons, the isolation requirement is that the total $p_T$ of all charged particles ($p_{\text{ch}}$), $\sum p_T$, with $\Delta R(e, p_{\text{ch}}) < 0.3$ should be less than 10% of the electron $p_T$. Similarly for muons, $\sum p_T$ for all particles with $\Delta R(\mu, p) < 0.4$ is required to be less than 6% of the muon $p_T$, but in addition, $\sum p_T$ is required to be less than $4 \times p_T \times 0.02$.}. The typical fiducial acceptance of the

$\Delta R(l, jet) > 1.5$. The expected isolation of the $b$-tagged jet from the
FIG. 1: Illustration of the usage of large-radius jet mass to veto \( t\bar{t} \) background. For the signal \( \tilde{T} \to Wb \), the \( b \)-quark recoils against the \( W \)-boson. Thus the hardest large-radius jet in the event typically contains a \( b \)-hadron plus additional soft and collinear radiation, and tends to have a low mass. For the semi-leptonic \( t\bar{t} \) background, right, a mildly boosted hadronically decaying top quark produces large-radius jets containing a significant fraction of the top decay products. The fraction of top decay products contained, and therefore the jet mass, increases with jet \( p_T \). Hence, after requiring a matching between a small-radius \( b \)-jet and large-radius jet, a cut based on the large-radius jet \( p_T \) and mass can be optimised to distinguish between signal and \( t\bar{t} \) background, whilst still retaining good signal efficiency.

\( \tilde{T} \) decay can be exploited further by vetoing events with extra central jets (those with \(|\eta| < 2.4\)) above a certain \( p_T \) threshold. Theoretical uncertainties on the production of extra jets decrease for higher thresholds. Hence, this cut was optimised by looking for both the largest \( S/\sqrt{B} \) and the largest jet \( p_T \) threshold. The optimal threshold was found to be 75 GeV. Finally, events must have at least one jet with \( p_T \geq 35 \) GeV and \( 2.5 < |\eta| < 4.5 \), consistent with the single top partner production mechanism.

In Table I the number of expected events for \( 20 \) fb\(^{-1} \) integrated luminosity at the 8 TeV LHC is shown at the preselection and final selection stages. The selection cuts lead to a \( S/B \) of 0.33 and \( S/\sqrt{B} \) of 3.0 for a 700 GeV \( \tilde{T} \).

To search for \( \tilde{T} \) production, a candidate \( \tilde{T} \)-mass constructed from the charged lepton and the \( b \)-jet and neutrino candidates is used. The \( b \)-tagged small-radius jet, that is matched to the large radius jet, is used as the \( b \)-jet candidate. The neutrino candidate is constructed from the \( E_\text{miss} \) and charged lepton by imposing a \( W \)-mass constraint on the lepton+ \( E_\text{miss} \) system [20]. The resulting \( \tilde{T} \)-candidate mass distribution is shown for signal and backgrounds in Figure 2. The signal distributions peak close to the \( \tilde{T} \) mass while background distributions turn over at lower masses.

RESULTS

In order to estimate whether a singly-produced top partner can be excluded with data collected at the LHC, we use a binned log-likelihood hypothesis test as described in Ref. [31]. The results of this procedure, as a function of integrated luminosity for the 8 TeV LHC data, are presented in Figure 3 which shows the confidence level at which single production of a 700 GeV \( \tilde{T} \) quark can be excluded in the absence of signal. These results are shown both before and after the forward-jet requirement and for different assumed levels of systematic uncertainty on the backgrounds: 0%, 5% and 10%. It can be seen that the sensitivity is greatly improved by the forward-jet requirement and that the full selection is sufficient to exclude the single-top partner production even for the most pessimistic assumed systematic uncertainty. Although this systematic treatment is rather simplistic we expect the search strategy to retain sufficient sensitivity to exclude the 700 GeV \( \tilde{T} \) if deployed in a real experimental analysis.
|                      | Number of events after preselection | Number of events after final selection |
|----------------------|--------------------------------------|---------------------------------------|
| Single top           | 6360                                 | 40                                    |
| W+jets               | 2.61\times10^6                      | 26                                    |
| tt                   | 4.72\times10^5                      | 13                                    |
| Total Background     | 3.09\times10^6                      | 76                                    |
| Signal \((m(T) = 700 \text{ GeV})\) | 574                                 | 26                                    |
| \(S/B\)             | 1.8\times10^5                       | 0.34                                  |
| \(S/\sqrt{B}\)      | 0.33                                 | 3.0                                   |

**TABLE I:** The number of expected events for an integrated luminosity of \(20 \text{ fb}^{-1}\) at the 8 TeV LHC.

**FIG. 3:** The results of the limit-setting procedure when applied to the search for a 700 GeV \(\tilde{T}\) using 8 TeV data. The results without requiring a forward jet (left) can be directly compared to the results with a forward jet requirement (right).

**SUMMARY, CONCLUSIONS AND OUTLOOK**

This is the first study to demonstrate a simple and feasible strategy for discovering single production of a top partner in the \(\tilde{T} \to Wb\) channel. The study shows that use of a forward jet and the requirement of a low-mass central large-radius jet and central jet veto are powerful tools for rejecting the SM background processes whilst retaining acceptable signal efficiency. This analysis is indicative that single production of 700 GeV top partners could be excluded already at the 8 TeV LHC. The mass reach of searches at higher-energy LHC running is likely to be significantly extended. We reserve study of \(\tilde{T} \to tH\) and \(\tilde{T} \to tZ\) for a future work, noting that in most searches the extra efficiency in a dominant decay channel outweigh cleanliness of background.

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