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### *Top partner probes of extended Higgs sectors*

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## Top Partner Probes of Extended Higgs Sectors

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**ABSTRACT:** Natural theories of the weak scale often include fermionic partners of the top quark. If the electroweak symmetry breaking sector contains scalars beyond a single Higgs doublet, then top partners can have sizable branching ratios to these extended Higgs sector states. In fact, top partner decays may provide the most promising discovery mode for such scalars, especially given the large backgrounds to direct and associated production. In this paper, we present a search strategy for top partner decays to a charged Higgs boson and a bottom quark, focusing on the case where the charged Higgs dominantly decays to third-generation quarks to yield a multi- $b$  final state. We also discuss ways to extend this search to exotic neutral scalars decaying to bottom quark pairs.

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## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Charged Higgs Discovery Channels</b>	<b>3</b>
2.1	Via Top Quark Associated Production	3
2.2	Via Fermionic Top Partner Decays	4
<b>3</b>	<b>Search Strategy</b>	<b>6</b>
3.1	Simulation Framework	6
3.2	Event Selection Criteria	8
3.3	Results	11
<b>4</b>	<b>Applicability to Neutral Scalars</b>	<b>15</b>
<b>5</b>	<b>Conclusions</b>	<b>16</b>

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## 1 Introduction

With the discovery of a 125 GeV Higgs boson at the LHC, we are getting our first glimpse at the origin of electroweak symmetry breaking (EWSB). If naturalness is a reliable guide, then we expect additional dynamics at the TeV scale to regulate quadratic divergences in the Higgs potential. In the Standard Model (SM), the large top quark Yukawa coupling induces large radiative corrections to  $m_h^2$ . Consequently, models of new physics generally involve new colored particles, top partners, to cancel these quadratic divergences. In the case where the Higgs is a pseudo-Nambu-Goldstone boson (PNGB), such top partners are fermionic.

Another common feature of new physics models is an extended Higgs sector, which often involves a second Higgs doublet or additional singlet scalars. This feature is particularly prevalent when the Higgs arises as a PNGB, since the breaking of a global symmetry  $G \rightarrow H$  often gives rise to more than just a single complex Higgs doublet. Because these extended scalars states typically carry only electroweak quantum numbers, they have small direct production cross sections at hadron colliders like the LHC. Therefore, it is important to explore new search strategies in order to fully investigate the possible dynamics of EWSB.

In this paper, we show how top partners can open additional discovery channels for extended Higgs sectors. In particular, top partners can be copiously pair-produced at the LHC through QCD processes, and the decay of top partners may provide the best avenue for observing additional scalars. For concreteness, we will focus on the decay of a top partner  $T$  to a charged Higgs  $H^\pm$  and a bottom quark  $b$ ,

$$T \rightarrow bH^\pm, \quad H^\pm \rightarrow tb, \quad (1.1)$$

where we utilize the charged Higgs decay mode that typically dominates for  $m_{H^\pm} > m_t + m_b$ . We will also show how the same search strategy is sensitive to neutral singlets  $\varphi^0$  via

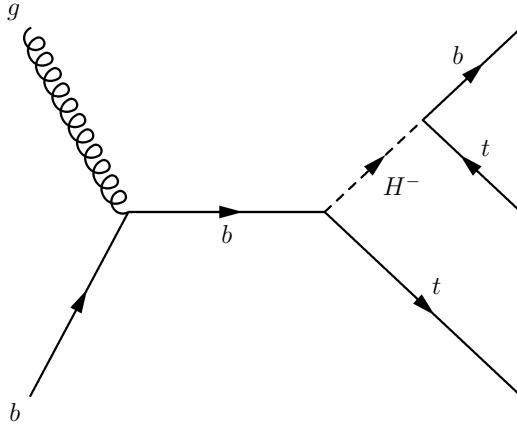
$$T \rightarrow t\varphi^0, \quad \varphi^0 \rightarrow bb. \quad (1.2)$$

However, we wish to emphasize a more general point: *if new top partners are found, searches for exotic decays to scalars should be a priority.* Our approach shares some intellectual ancestry with strategies to find Higgs bosons through supersymmetric particle decays [1, 2], as well as studies designed to pick out the SM Higgs boson from top partner decays using jet substructure techniques [3].

Previous studies of the detectability of charged Higgs states with  $m_{H^\pm} > m_t + m_b$  have focused on top quark associated production  $gb \rightarrow tH^\pm$  [4, 5]. The cross section for this process can in principle be large because extended Higgs sector states often have significant couplings to top quarks. However, as we will review, there are a number of obstacles that make this search challenging. Assuming top partners exist, we will show how pair production of top partners followed by the decay  $T \rightarrow bH^\pm$  can be a complementary search strategy. Should these exotic top partner decays be observed, they will become an important window to the structure of new physics at the TeV scale.

The proposed search is particularly well-motivated by little Higgs (LH) scenarios [6–10], which prominently feature both top partners and extended Higgs sectors [11]. In fact, LH models often contain more top partners than strictly necessary to regulate the Higgs potential, perhaps because of an underlying custodial symmetry [12–14] or an enhanced global symmetry of the strong dynamics [15, 16]. The search described here is relevant for standard top partners as well as their exotic cousins. Similarly, as emphasized in Ref. [17], the scalar sector of LH models must contain more than just a single Higgs doublet. At minimum, additional scalars are necessary to achieve the desired quartic potential for the Higgs boson. Moreover, unless the theory has a symmetry like  $T$ -parity [18, 19], precision electroweak constraints plus the model building constraint of “dangerous singlets” imply the presence of at least two Higgs doublets [17]. While we are motivated by LH models, the phenomenology we discuss in this paper is relevant for any theory with exotic top-like states and extended Higgs sectors. For example, similar phenomenology can be present in heavy fourth generation models with multiple Higgs doublets as long as the dominant mixing is with the third generation [20, 21].

The remainder of this paper is organized as follows. In Sec. 2, we compare the discovery prospects for a charged Higgs boson via top quark associated production  $pp \rightarrow tH^\pm$  versus top partner decay  $T \rightarrow bH^\pm$ . In Sec. 3, we demonstrate a viable search strategy designed to uncover  $T \rightarrow bH^\pm$ , using realistic detector modeling and matched Monte Carlo samples to estimate the backgrounds. We show in Sec. 4 how the same search is applicable for other scalar states that may be produced in top partners decays, such as  $T \rightarrow t\varphi^0$  with  $\varphi^0 \rightarrow bb$ . We conclude in Sec. 5 with possible extensions of our analysis.



**Figure 1:** Feynman diagram contributing to  $gb \rightarrow tH^\pm$  with  $H^\pm \rightarrow tb$  decay.

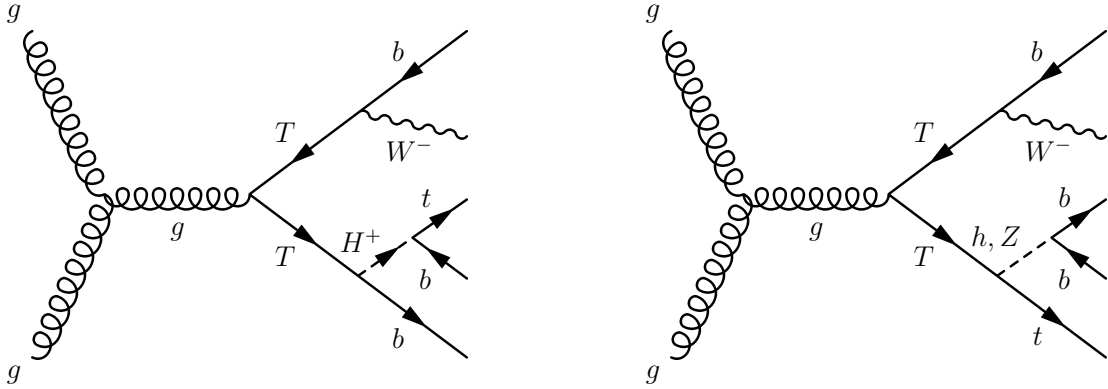
## 2 Charged Higgs Discovery Channels

Many models with extended Higgs sectors contain a charged Higgs state  $H^\pm$  with a potentially large  $H^\pm \rightarrow tb$  branching ratio. For example, in a Type II two Higgs doublet model (2HDM), the absence of a measured deviation from the SM prediction for  $b \rightarrow s\gamma$  indicates that the charged Higgs bosons must be somewhat heavy,  $m_{H^\pm} \gtrsim 300$  GeV [22, 23], ensuring the  $H^\pm \rightarrow tb$  decay mode is open. Indeed, for such heavy charged Higgs bosons,  $H^\pm \rightarrow tb$  dominates over much of the parameter space. In this paper, we assume for simplicity that the branching ratio  $\text{Br}(H^\pm \rightarrow tb) = 1$ . We briefly comment on the possibility of other useful decay modes in the conclusion. We highlight the main obstacles to observing  $pp \rightarrow tH^\pm$  in Sec. 2.1, and then discuss the potential advantages of the decay  $T \rightarrow bH^\pm$  in Sec. 2.2.

### 2.1 Via Top Quark Associated Production

There can be appreciable production of  $H^\pm$  in association with a top quark via  $gb \rightarrow tH^\pm$  (see Fig. 1), enabling a search for  $H^\pm \rightarrow tb$  in the  $t\bar{t}b$  final state. In particular, the final states in which a single top decays leptonically allow for the reconstruction of both tops (with reduced combinatoric background relative to the dileptonic or dihadronic final states) and thus the potential observation of a  $H^\pm$  resonance peak in the  $m_{t\bar{t}}$  distribution.

Unfortunately, this channel is subject to large SM backgrounds from  $t\bar{t}$ +jets (with a light jet faking a  $b$ ) and  $t\bar{t}b\bar{b}$ . One might hope that the  $t\bar{t}$ +jets background could be avoided by requiring 3  $b$ -tagged jets in the final state, as advocated in Refs. [4, 5, 24] and studied at the detector level in Ref. [25]. However,  $t\bar{t}$ +jets is still a formidable background even after 3  $b$ -tagged jets are required, in part because there is a relatively high charm mistag rate ( $\epsilon_c \approx 0.14$  [26, 27] as opposed to  $\epsilon_c \approx 0.01$  as assumed in Refs. [4, 5, 24, 25]), and in part because there is a non-negligible probability for QCD jet combinations to exhibit significant invariant masses (i.e.  $m_{jj} \sim m_W$  or  $m_{jjj} \sim m_t$ ). Alternatively, one could attempt to search for a charged Higgs in a  $t\bar{t}b\bar{b}$  final state from  $pp \rightarrow tH^\pm b$ , with the requirement of 4  $b$ -tagged jets in the



**Figure 2:** Feynman diagrams contributing to top partner pair production, with top partners decaying to yield a  $4b$ ,  $2W^\pm$  final state. Our signal, containing decays of the type  $T \rightarrow bH^\pm \rightarrow btb$  (left), potentially has a background from the decays  $T \rightarrow tZ, th \rightarrow tbb$  (right).

final state as suggested in Ref. [28]. Requiring an additional  $b$ -jet does suppress the  $tt$ +jets background. However, the additional  $b$ -jet produced in  $pp \rightarrow tH^\pm b$  is frequently relatively soft, suppressing the signal process if typical  $b$ -jet  $p_T$  criteria are imposed. Furthermore, even if the  $tt$ +jets background can be reduced to acceptable levels via this strategy, there is an irreducible background due to SM  $ttbb$  production. Consequently, even using sophisticated techniques to distinguish signal from background, the reach of this search strategy remains limited. The discovery reach found in Ref. [29] is  $\tan \beta \gtrsim 50$  for  $m_{H^\pm} = 500$  GeV in a Type II 2HDM.<sup>1</sup> Comparing with Ref. [30], this corresponds roughly to  $\sigma(pp \rightarrow tH^\pm) \gtrsim 700$  fb.

Thus, the discovery of a charged Higgs boson via top quark associated production seems extremely challenging, particularly for intermediate  $\tan \beta$  and larger  $m_{H^\pm}$ .<sup>2</sup> This motivates an investigation of alternative methods for searching for charged Higgses.

## 2.2 Via Fermionic Top Partner Decays

In this paper, we advocate an alternative method for observing  $H^\pm$  at the LHC, namely in the decays of fermionic top partners. Colored top partners can be copiously produced at hadron colliders via QCD processes  $pp \rightarrow TT$  as shown in Fig. 2.<sup>3</sup> If the branching ratio for  $T \rightarrow bH^\pm$  is non-negligible, top partner decays can yield a significant number of events containing at least one  $H^\pm$ , potentially permitting discovery. Since the  $T \rightarrow bH^\pm$  branching ratio is not necessarily suppressed at intermediate values of  $\tan \beta$  (but rather depends on specific model-building details), searches in this channel can complement top quark associated production searches outlined above.

<sup>1</sup>Ref. [29] assumed a conservative  $b$ -tagging efficiency of  $\epsilon_b = 0.5$ , so the reach might improve somewhat with better  $b$ -tagging.

<sup>2</sup>For much larger values of  $m_{H^\pm} \gtrsim 1$  TeV, jet substructure techniques may offer some improvement [31].

<sup>3</sup>For very large  $m_T \gtrsim 1$  TeV, single top partner production may dominate [32], favoring alternative search strategies.

Like the SM top fields, top partners are generally electroweak singlets or doublets, permitting renormalizable Yukawa couplings between a top partner, the Higgs field, and a SM top quark. Consequently, top partners will typically exhibit decays to SM particles through these couplings:

$$T \rightarrow bW^\pm, tZ, th. \quad (2.1)$$

Decays involving non-SM particles, such as  $T \rightarrow bH^\pm$ , are generally expected to be subdominant due to phase space suppression. The exclusively SM decay modes in Eq. (2.1) have been extensively studied as possible discovery channels for top partners [32–35], and recent limits from the LHC have been set in Refs. [36, 37].

We envision a scenario where the top partner  $T$  is discovered—hopefully soon—via one of the decay modes in Eq. (2.1). We then have the opportunity to search for subdominant decays like  $T \rightarrow bH^\pm$ . In fact, when top partners are pair produced in  $pp \rightarrow TT$ , one can use a decay mode like  $T \rightarrow bW^\pm$  to “tag” events as potential top partner pair events and thereby reduce SM backgrounds (notably, events with lighter SM tops). For concreteness, consider the event topology in Fig. 2,<sup>4</sup>

$$pp \rightarrow (T \rightarrow bW_{\text{had}}^\pm)(T \rightarrow bH^\pm \rightarrow bt_{\text{lep}}b) \rightarrow 4b + 2j + \ell^\pm\nu, \quad (2.2)$$

where the subscript “had” (“lep”) refers to decays of the corresponding  $W^\pm$  to  $jj$  ( $\ell^\pm\nu$ ). As the  $W^\pm$  from the  $T \rightarrow bW_{\text{had}}^\pm$  decay will be relatively boosted, its hadronic decay will yield a distinctive signature of two fairly collimated jets with  $m_{jj} \sim m_W$  that reconstruct a top partner with a  $b$ -jet. Meanwhile, the leptonic decay on the other side of the event reduces combinatoric background, allowing a reconstruction of a second top partner in the event.

The dominant SM backgrounds are  $t\bar{t}b\bar{b}$  and  $t\bar{t}$ +jets with two light jets faking  $b$ ’s. However, the presence of four relatively hard  $b$ -jets in the signal means that a requirement of four  $b$ -tagged jets can be used (in addition to top partner reconstruction) to greatly suppress these backgrounds. The low fake rate suppresses  $t\bar{t}$ +jets, whereas  $t\bar{t}b\bar{b}$  can be effectively suppressed since the additional  $b$ ’s often come from gluon splitting, such that frequently either one  $b$ -jet is soft and does not pass a minimum  $p_{T,j}$  requirement, or the  $b$ ’s are collimated and consequently coalesce into a single jet. High  $b$ -multiplicity requirements have similarly been applied to reduce  $t\bar{t}$ +jets and  $t\bar{t}b\bar{b}$  backgrounds in the context of SUSY stop searches [38] and searches for top partners decaying to exclusively SM states [39].

With the SM background under control, a remaining challenge is that other top partner decays can yield the same final state as Eq. (2.2), notably  $T \rightarrow t_{\text{lep}}h\bar{b}b$  and  $T \rightarrow t_{\text{lep}}Z\bar{b}b$  (see Fig. 2). These “background” events exhibit a key kinematic difference, however, since the  $b\bar{b}$ -pair from the  $h$  or  $Z$  is constrained to have an invariant mass of  $m_{b\bar{b}} = m_h$  or  $m_Z$ . For signal events the  $b\bar{b}$  invariant mass can be much larger. Consequently, we will see that a cut on the minimum  $m_{b\bar{b}}$  in the event can be used to efficiently isolate rare  $T \rightarrow bH^\pm$  decays. As long as the branching ratio  $T \rightarrow bH^\pm$  is of order 10%, then the search presented below will be sensitive to the  $bH^\pm$  states.

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<sup>4</sup>For simplicity, we do not distinguish between particles and anti-particles when writing decay chains.

### 3 Search Strategy

In this section, we describe a search strategy that can be used to discover the presence of a charged Higgs produced in  $T \rightarrow bH^\pm$  based on the topology described in Sec. 2.2. As a benchmark, we choose  $m_T = 700$  GeV, a representative value that satisfies current bounds [36, 37, 40] but is not so high as to create tensions with naturalness. Since a  $H^\pm$  discovery will require high luminosity ( $\simeq 300 \text{ fb}^{-1}$ ), we consider events for the LHC with  $\sqrt{s} = 14$  TeV.

We first describe some of the details of our simulation framework, and then present possible event selection criteria that can identify a reasonable fraction of  $T \rightarrow bH^\pm$  events while rejecting much of the SM and  $T \rightarrow th, tZ$  backgrounds.

#### 3.1 Simulation Framework

For our study, we use MADGRAPH 5 [41] to generate parton-level events, interfaced with PYTHIA 6.4 [42] for decay and hadronization. For top partner pair production, we generate MLM-matched [43, 44] samples of

$$pp \rightarrow TT + nj \tag{3.1}$$

with  $n = 0, 1, 2$  and top partners decaying as

$$T \rightarrow bW^\pm, \quad th, \quad tZ, \quad bH^\pm \tag{3.2}$$

in MADGRAPH – subsequent decays are carried out in PYTHIA. Using unmatched samples, we have confirmed that we obtain similar results by (1) simulating the full  $TT \rightarrow bW^\pm X \rightarrow bbbbjj\ell\nu$  ( $X = bH^\pm, th, tZ$ ) decay chain in MADGRAPH and (2) simulating  $TT \rightarrow bW^\pm X$  in MADGRAPH with subsequent decays in PYTHIA, indicating that the latter method should indeed be sufficient for the matched samples. For the benchmark value of  $m_T = 700$  GeV, the MADGRAPH matched cross section is

$$\sigma_{\text{MLM}}(pp \rightarrow TT + nj, m_T = 700 \text{ GeV}) = 470 \text{ fb}. \tag{3.3}$$

For the dominant SM backgrounds, we generate MLM-matched samples of  $pp \rightarrow tt + nj$  for  $n = 0, 1, 2$  in the four-flavor scheme and unmatched samples of  $pp \rightarrow ttbb$ . The production cross sections from MADGRAPH for the SM processes are

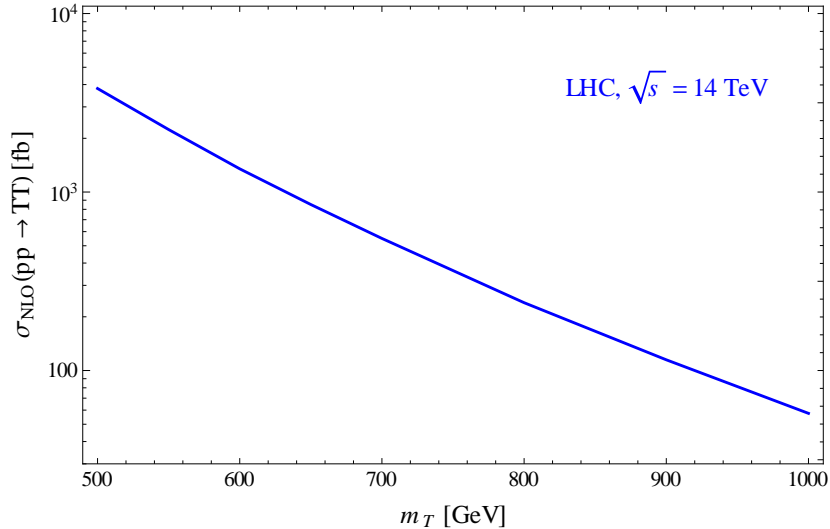
$$\sigma_{\text{MLM}}(pp \rightarrow tt + nj) = 700 \text{ pb}, \tag{3.4}$$

$$\sigma(pp \rightarrow ttbb) = 10.3 \text{ pb}. \tag{3.5}$$

All of the processes considered above are subject to sizable higher-order QCD corrections. At NLO for the 14 TeV LHC, HATHOR [45] gives inclusive cross sections (see Fig. 3)

$$\sigma_{\text{incl}}(pp \rightarrow tt) = 900 \text{ pb}, \tag{3.6}$$

$$\sigma_{\text{incl}}(pp \rightarrow TT, m_T = 700 \text{ GeV}) = 600 \text{ fb}, \tag{3.7}$$



**Figure 3:** Cross section for inclusive top partner pair production  $pp \rightarrow TT$  at the LHC with  $\sqrt{s} = 14$  TeV as a function of top partner mass  $m_T$  (from Ref. [45]). For our studies, we use the benchmark value  $m_T = 700$  GeV.

so we apply a  $K$ -factor of  $K \approx 1.3$  to the  $tt$ +jets and  $TT$ +jets samples. The appropriate  $K$ -factor for  $t\bar{t}b\bar{b}$  is less readily determined, but since the  $t\bar{t}b\bar{b}$  and  $tt$ +jets backgrounds are ultimately comparable, we also apply  $K = 1.3$  to  $t\bar{t}b\bar{b}$  to avoid significantly underestimating the  $t\bar{t}b\bar{b}$  background. As the realistic  $K$ -factor for  $t\bar{t}b\bar{b}$  is likely less than that for  $tt$ +jets, this is a somewhat conservative choice.

Both the signal and background processes will contain two  $W$  bosons from top or top partner decay. As we will require events to contain one hard, isolated lepton which can be used to trigger the event, we allow the  $W$  pair to decay via all channels capable of yielding  $jj\ell\cancel{E}_T$ , namely

$$WW \rightarrow (jj \text{ or } \tau\nu_\tau)(\ell\nu \text{ or } \tau\nu_\tau) \quad (3.8)$$

where the lepton or jets may arise from  $\tau$  decay. In particular, we do not account for fake leptons in this analysis, which are expected to be a small effect.

Detector simulation was carried out using DELPHES 2.0.3 [46] (with [47, 48]) including jet clustering with FASTJET [49], using resolution parameters appropriate for the ATLAS detector. Data analysis was performed using ROOT [50]. Electrons are required to have  $p_{T,e} > 20$  GeV and  $|\eta| < 2.47$  (excluding the barrel to endcap transition region  $1.37 < |\eta| < 1.52$ ). Muons are required to have  $p_{T,\mu} > 20$  GeV and  $|\eta| < 2.5$ . Furthermore, isolation criteria are imposed. Electrons are isolated if the transverse momentum deposited in an isolation cone of radius  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ ,  $p_T^{\Delta R < 0.2} < 4$  GeV. Isolated muons are also required to have  $p_T^{\Delta R < 0.2} < 4$  GeV, and in addition are required to be a distance  $\Delta R > 0.4$  from any jet with  $p_{T,j} > 20$  GeV (to suppress leptons from heavy-flavor decays inside jets). Jets are clustered using the anti- $k_T$  algorithm [51] with  $R = 0.4$  and are required

to have  $p_{T,j} > 20$  GeV,  $|\eta| < 2.5$ . These criteria are similar to those used in ATLAS searches for comparable final states [36, 52].

For  $b$ -tag, light ( $u, d, s$ ) jet mistag, and  $c$ -mistag efficiencies, we use the functions given in Ref. [39] as suitable fits to the measured efficiencies [26, 27], namely

$$\epsilon_b = 0.6 \tanh\left(\frac{p_T}{36 \text{ GeV}}\right) \times (1.02 - 0.02 |\eta|), \quad (3.9)$$

$$\epsilon_j = 0.001 + 0.00005 \frac{p_T}{\text{GeV}}, \quad (3.10)$$

$$\epsilon_c = 0.14, \quad (3.11)$$

respectively. In order to reduce the required number of generated events to achieve reasonable statistics (particularly for the  $tt$ +jets background), we consider all possible tagging configurations for any given event and weight each configuration appropriately, as opposed to implementing  $b$ -tagging (and mis-tagging) at the level of the detector simulation.<sup>5</sup>

### 3.2 Event Selection Criteria

The signal in Eq. (2.2) is characterized by a high multiplicity of relatively hard jets (including four  $b$ -jets), a lepton, and missing energy. The hardest  $b$  will be quite hard as it likely arises from the  $T \rightarrow bW_{\text{had}}^\pm$  decay. Since the neutrino arises at the end of a longer decay chain, the signal is not characterized by particularly large missing energy, though a mild  $\cancel{E}_T$  cut can still help reduce backgrounds. We perform the following basic cuts to select events of this type:

1. Exactly 1 isolated lepton ( $p_{T,\ell} > 20$  GeV);
2. Missing energy  $\cancel{E}_T > 20$  GeV;
3. Event contains  $\geq 4$   $b$ -tagged jets and  $\geq 2$  untagged jets ( $p_{T,j} > 20$  GeV);
4. Transverse momentum of the hardest  $b$ -jet satisfies  $p_{T,b_1} > 160$  GeV;
5.  $m_{\text{eff}} > 1.2$  TeV, where  $m_{\text{eff}} = \sum_j p_{T,j} + p_{T,\ell} + \cancel{E}_T$ , and the sum runs over all of the jets in the event.

As shown later in Table 1, these cuts reduce the SM backgrounds by orders of magnitude relative to the events containing top partners. The exact values chosen give good top partner-to-SM background discrimination for  $m_T = 700$  GeV, but should be adjusted depending on the measured value of  $m_T$  (which, as mentioned in Sec. 2.2, we assume has been measured via a dominant decay mode).

To further suppress the  $tt$ +jets and  $ttbb$  backgrounds and to isolate top partner pair production events containing  $T \rightarrow bH^\pm$  decays, we apply the following invariant mass cuts:

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<sup>5</sup>We do not include the effects of event pileup in this study. Our expectation is that pileup would be most important in the reconstruction of the hadronic  $W$  (see cut 7 below). However, since the  $W$  is at reasonably high  $p_T$ , some additional handles, including possibly jet substructure techniques, may be able to reject fake  $W$ 's from pileup jets.

6. Smallest invariant mass for two  $b$ -tagged jets in the event satisfies  $\min(m_{bb}) > 150$  GeV. As already mentioned at the end of Sec. 2.2, this helps suppress the background of  $T \rightarrow th$  and  $T \rightarrow tZ$ , but as discussed more below it also helps control the SM backgrounds.
7. Hardest  $b$ -tagged jet (denoted  $b_1$ ) and two untagged jets have invariant mass  $m_{b_1jj} \approx m_T$ , with the two untagged jets required to have  $m_{jj} \approx m_W$  and somewhat small  $\Delta R_{jj}$ . For the case of  $m_T = 700$  GeV, we require  $m_{b_1jj} \in [600, 750]$  GeV with  $m_{jj} = m_W \pm 20$  GeV and  $\Delta R_{jj} < 1.5$ .
8. Event should contain three additional  $b$ -tagged jets (denoted  $b_{2,3,4}$ ) that, together with the lepton and missing energy (from the neutrino), reconstruct a second top partner, i.e. satisfying  $m_{b_2b_3b_4\cancel{E}_T} \approx m_T$ . For  $m_T = 700$  GeV, we require  $m_{b_2b_3b_4\cancel{E}_T} \in [500, 800]$  GeV.

The existence (or absence) of a charged Higgs state with significant coupling to top partners could be inferred from an excess (or lack of excess) of events passing these cuts.

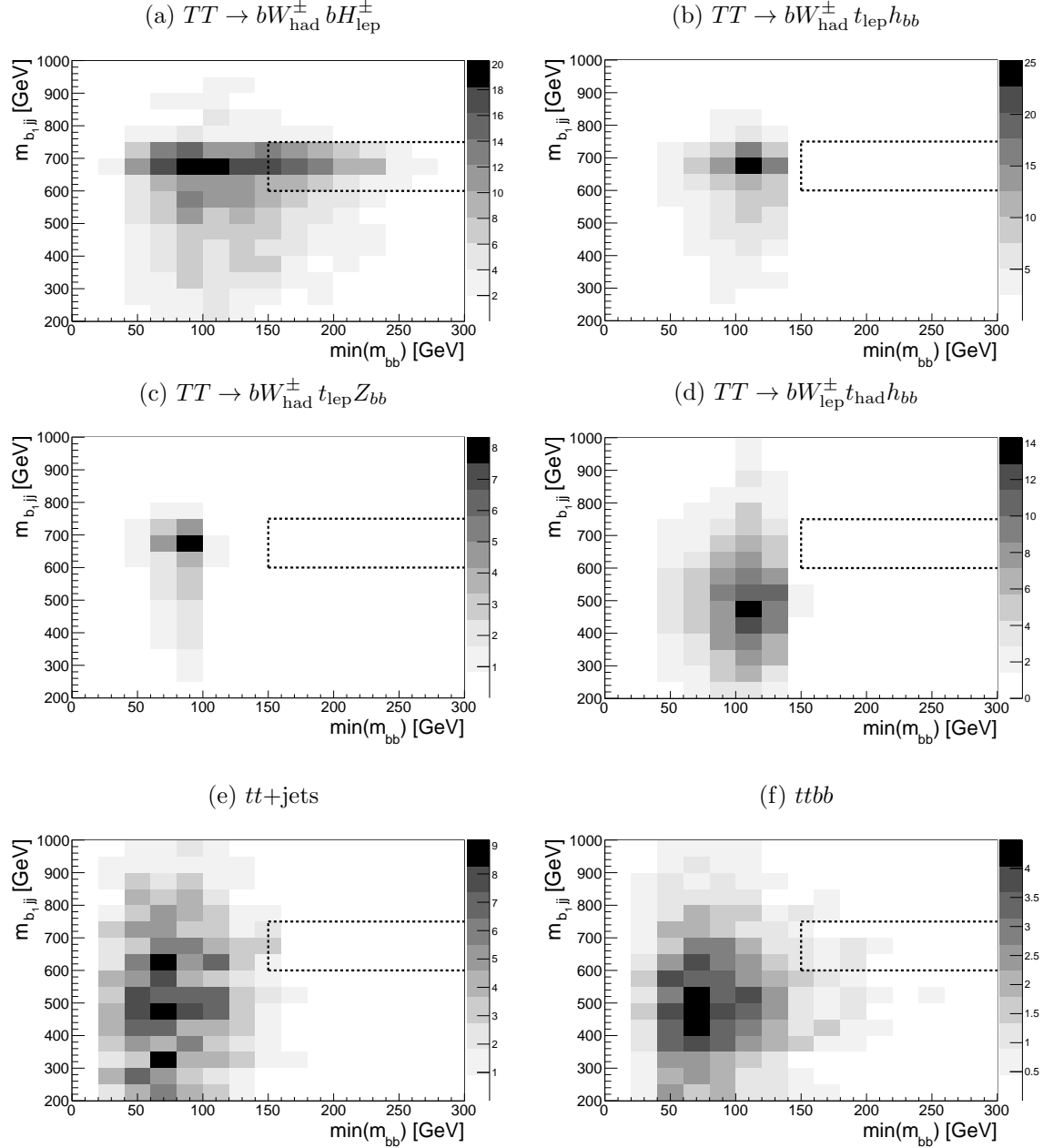
While cut 6 was designed to reject events with  $h/Z \rightarrow bb$ , it is effective at rejecting  $ttjj$  and  $tbb$  events as well. For the  $tbb$  background, this is because the relatively collimated  $b$ 's from gluon splitting can exhibit low invariant mass. For the  $tt$ +jets background, this cut rejects events where one of the quarks from the hadronic top decay is mistagged as a  $b$ -jet; due to the relatively large  $\epsilon_c$ , this can be particularly valuable in suppressing the background events with a mis-tagged charm from  $W^\pm \rightarrow cs$ . In the decay of a top quark  $t \rightarrow bqq'$  where  $q$  is mistagged as a  $b$ -jet

$$m_{bq}^2 = (p_b + p_q)^2 = (p_t - p_{q'})^2 = m_t^2 - 2p_t \cdot p_{q'} = m_t^2 - 2m_t E_{q'} \leq m_t^2, \quad (3.12)$$

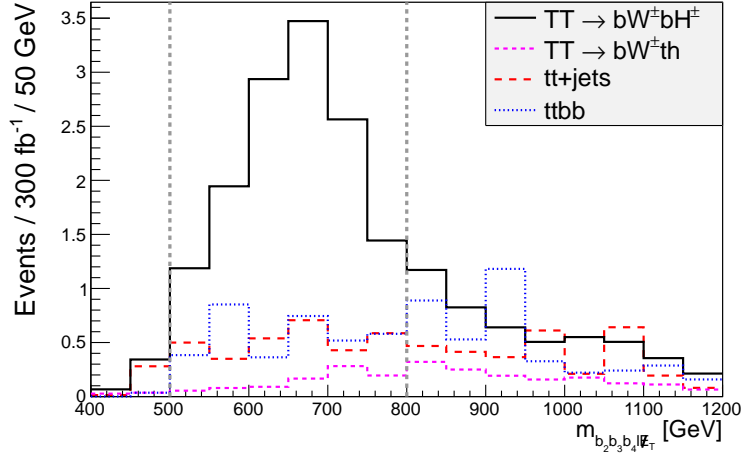
where  $E_{q'}$  is the energy of  $q'$  in the rest frame of the top quark. So, a sufficiently hard cut on  $\min(m_{bb})$  can help mitigate SM backgrounds that yield the same  $bbbbjj\ell\nu$  final state. Since the majority of events are not expected to saturate the bound, we choose the cut  $\min(m_{bb}) > 150$  GeV  $> m_h, m_Z$  as a compromise between rejecting backgrounds and accepting signal events, some of which have coincidentally small  $\min(m_{bb})$ .

To demonstrate how these invariant mass cuts are effective, Fig. 4 shows distributions of  $\min(m_{bb})$  (cut 6) versus  $m_{b_1jj}$  (cut 7) for a variety of top partner processes and SM backgrounds after applying only basic cuts.<sup>6</sup> We take  $m_T = 700$  GeV and  $m_{H^\pm} = 500$  GeV, and the benchmark cuts maintain a good fraction of the signal topology in Eq. (2.2). The cut on  $m_{b_1jj} \approx m_T$  serves to isolate top partner events with a  $T \rightarrow bW_{\text{had}}^\pm$  decay. The top partner clearly shows up as a band in the  $m_{b_1jj}$  distribution in panels Fig. 4a–Fig. 4c. Furthermore, whereas Fig. 4b and Fig. 4c are peaked at  $(m_{b_1jj}, \min(m_{bb})) \approx (m_T, m_{h,Z})$ , Fig. 4a exhibits a band at  $m_{b_1jj} \approx m_T$  with  $\min(m_{bb})$  extending over a range of values including  $\min(m_{bb}) > m_{h,Z}$ . As a result, the cut on  $\min(m_{bb})$  isolates the  $T \rightarrow bH^\pm$  decay

<sup>6</sup>As described in cut 7,  $m_{b_1jj}$  is only shown if there is an untagged jet pair satisfying  $m_{jj} = m_W \pm 20$  GeV and  $\Delta R_{jj} < 1.5$ .



**Figure 4:** Distributions of  $\min(m_{bb})$  against  $m_{b_{1jj}}$  after applying basic cuts (1–5), for  $m_T = 700$  GeV,  $m_{H^\pm} = 500$  GeV. Here,  $m_{b_{1jj}}$  corresponds to all untagged jet pairs satisfying  $m_{jj} = m_W \pm 20$  GeV and  $\Delta R_{jj} < 1.5$ . Dashed lines denote the signal region (cuts 6 and 7). For Fig. 4a through Fig. 4d, grayscale represent Events/ $\text{Br}_{bWX}$  [ $300 \text{ fb}^{-1}$ ], where  $\text{Br}_{bWX}$  denotes the branching ratio for the process  $TT \rightarrow bW^\pm X$ . For Fig. 4e and Fig. 4f, grayscale represents Events [ $300 \text{ fb}^{-1}$ ].



**Figure 5:** Distribution of  $m_{b_2 b_3 b_4 \ell \cancel{E}_T}$  after cuts 1 through 7 have been applied. As in Fig. 4,  $m_T = 700$  GeV and  $m_{H^\pm} = 500$  GeV, and in addition we take  $\text{Br}_{bWbH^\pm} = 0.1$  and  $\text{Br}_{bWth} = 0.2$ . The shape of the distribution for  $TT \rightarrow bW^\pm tZ$  is similar to that for  $TT \rightarrow bW^\pm th$ . Dashed lines denote the region selected by cut 8,  $m_{b_2 b_3 b_4 \ell \cancel{E}_T} \in [500, 800]$  GeV.

from other top partner decays. Also Fig. 4e and Fig. 4f demonstrate the efficacy of the  $m_{bb}$  cut against the SM backgrounds for the reasons described above. The process

$$pp \rightarrow (T \rightarrow bW_{\text{lep}}^\pm)(T \rightarrow bH_{\text{had}}^\pm) \quad (3.13)$$

is largely rejected by our cuts, but is counted as signal as it involves a charged Higgs.<sup>7</sup>

Distributions of  $m_{b_2 b_3 b_4 \ell \cancel{E}_T}$  are shown in Fig. 5 for the signal  $TT \rightarrow bW^\pm bH^\pm$  and dominant SM background processes after cuts 1 through 7 have been applied. The presence of a resonance structure at  $m_{b_2 b_3 b_4 \ell \cancel{E}_T} \approx m_T$  in the signal distribution means that cut 8 on  $m_{b_2 b_3 b_4 \ell \cancel{E}_T}$  can be used to isolate events with a second top partner and further reduce the SM backgrounds. Note that the sharpness of the signal peak is enhanced by cut 7 which helps to resolve combinatoric ambiguity.

### 3.3 Results

Efficiencies for the various cuts from Sec. 3.2 are shown in Table 1 for a representative heavy charged Higgs mass,  $m_{H^\pm} = 500$  GeV. For these efficiencies, the SM background contributions from  $tt$ +jets and  $ttbb$  are comparable. Also shown are the dominant background contributions arising from decays of top partners to electroweak bosons. In principle, top quark associated production of  $H^\pm$  is also a “background” (as it does not serve our goal of

<sup>7</sup>In principle, one could enhance the signal sensitivity by crafting a selection criteria designed for Eq. (3.13). We found only a marginal improvement, however, since it is harder to develop a good  $T \rightarrow bW_{\text{lep}}^\pm$  tag to reject the  $tt$ +jets background.

Process	$TT \rightarrow$	$TT \rightarrow$		SM	
	$bW^\pm bH^\pm$	$bW^\pm th$	$bW^\pm tZ$	$tt + nj$	$ttbb$
$\sigma \times \text{Br}$ [fb]	300 $\text{Br}_{bWbH^\pm}$	170 $\text{Br}_{bWth}$	44 $\text{Br}_{bWtZ}$	$4.4 \times 10^5$	$6.6 \times 10^3$
Basic Cuts	$3.6 \times 10^{-2}$	$3.0 \times 10^{-2}$	$2.6 \times 10^{-2}$	$7.4 \times 10^{-6}$	$1.6 \times 10^{-4}$
Cut 6: $\min(m_{bb})$	$1.3 \times 10^{-2}$	$2.4 \times 10^{-3}$	$2.1 \times 10^{-3}$	$6.1 \times 10^{-7}$	$2.8 \times 10^{-5}$
Cut 7: $m_{b_1jj}$	$2.2 \times 10^{-3}$	$2.6 \times 10^{-4}$	$2.3 \times 10^{-4}$	$5.4 \times 10^{-8}$	$4.1 \times 10^{-6}$
Cut 8: $m_{b_2b_3b_4\ell E_T}$	$1.5 \times 10^{-3}$	$8.4 \times 10^{-5}$	$5.7 \times 10^{-5}$	$2.3 \times 10^{-8}$	$1.7 \times 10^{-6}$
Events [300 $\text{fb}^{-1}$ ]	130 $\text{Br}_{bWbH^\pm}$	4.3 $\text{Br}_{bWth}$	0.76 $\text{Br}_{bWtZ}$	3.1	3.4

**Table 1:** Cumulative efficiencies for signal and background events to pass the selection criteria. Signals are generated for a representative heavy charged Higgs mass,  $m_{H^\pm} = 500$  GeV. In all events,  $W^\pm$  bosons decay as specified in Eq. (3.8), and the Higgs and  $Z$  bosons in these events decay to  $bb$ . We take  $\text{Br}(h \rightarrow bb) = 0.58$ ,  $\text{Br}(Z \rightarrow bb) = 0.15$ , and assume  $\text{Br}(H^\pm \rightarrow tb) = 1$ .  $\text{Br}_{bWX}$  denotes the branching ratio for  $TT \rightarrow bW^\pm X$ . The cut ranges are defined as  $\min(m_{bb}) > 150$  GeV (cut 6),  $m_{b_1jj} \in [600, 750]$  GeV (cut 7), and  $m_{b_2b_3b_4\ell E_T} \in [500, 800]$  (cut 8).

uncovering information about the  $H^\pm$  coupling to top partners), but it tends to be negligible unless  $\sigma(pp \rightarrow tH^\pm) \gtrsim \mathcal{O}(600)$  fb. In terms of the complementarity of these two channels as methods for searching for  $H^\pm$ , it is worth noting that this is exactly the region in which a top quark associated production search becomes potentially viable, see Sec. 2.1.

The discovery potential of this search depends on the branching ratios of the top partners. As an illustrative example, consider the parametrization

$$T \rightarrow \begin{cases} bH^\pm & \text{Br} = \epsilon \\ bW^\pm & \text{Br} = \frac{1}{2}(1 - \epsilon) \\ tZ & \text{Br} = \frac{1}{4}(1 - \epsilon) \\ th & \text{Br} = \frac{1}{4}(1 - \epsilon) \end{cases}. \quad (3.14)$$

The 2 : 1 : 1 ratio for the  $bW^\pm : tZ : th$  modes is what one might approximately expect due to the Goldstone Boson Equivalence Theorem [53–55]. Using the efficiencies in Table 1 for  $m_T = 700$  GeV,  $m_{H^\pm} = 500$  GeV, we find using Poisson statistics that with  $\mathcal{L} = 300 \text{ fb}^{-1}$  of integrated data, one can probe

$$\epsilon = \begin{cases} 0.04 & \text{at } 2\sigma \ (S = 5.5, B = 6.5_{\text{SM}} + 1.2 = 7.7) \\ 0.12 & \text{at } 5\sigma \ (S = 13.7, B = 6.5_{\text{SM}} + 1.0 = 7.5) \end{cases}, \quad (3.15)$$

indicating that this channel is viable even for relatively modest  $T \rightarrow bH^\pm$  branching ratios. The change in  $B$  results from the change in  $\text{Br}_{bWth, bWtZ}$  as a function of  $\epsilon$ , i.e. these decay processes contribute an expected 1.2 background events at  $\epsilon = 0.04$  but 1.0 events at an  $\epsilon = 0.12$ . In realistic 2HDMs with fermionic top partners, such as the ‘‘Bestest Little Higgs’’ [56], a wide variety of decay branching ratios are possible for the various top partners in

$m_T$	$m_{H^\pm}$	Efficiency	Events [ $\mathcal{L} = 300 \text{ fb}^{-1}$ ]	$\epsilon (2\sigma)$	$\epsilon (5\sigma)$
	400	$1.5 \times 10^{-3}$	130 $\text{Br}_{bWbH^\pm}$	0.04	0.12
700	500	$1.5 \times 10^{-3}$	130 $\text{Br}_{bWbH^\pm}$	0.04	0.12
	600	$8.2 \times 10^{-4}$	73 $\text{Br}_{bWbH^\pm}$	0.08	0.24

**Table 2:** Efficiencies for passing the given selection criteria for  $m_T = 700$  GeV and several representative values of  $m_{H^\pm}$ . Also shown are corresponding values of  $\epsilon$  (defined in Eq. (3.14)) yielding  $2\sigma$  and  $5\sigma$  significance assuming  $\text{Br}(H^\pm \rightarrow tb) = 1$  and  $\mathcal{L} = 300 \text{ fb}^{-1}$ . The  $2\sigma$  ( $5\sigma$ ) significances correspond to  $S \approx 5.5$  (13.7) and  $B \approx 7.7$  (7.5).

different regions of parameter space, making this channel worthy of exploration if fermionic top partners are discovered (for a sense of the various branching ratios possible in the “Bestest Little Higgs,” see Ref. [57]).

As we consider a signal process involving  $T \rightarrow bW^\pm \rightarrow bj\bar{j}$ , there is also in principle an upper limit on the  $\epsilon$  that can be probed using this approach, above which the channel would be suppressed by small  $\text{Br}(T \rightarrow bW^\pm)$ . We view this possibility as unlikely because, as mentioned, the  $T \rightarrow bH^\pm$  decay is likely to be subdominant due to phase space suppression. If the  $T \rightarrow bH^\pm$  decay does dominate, alternative search strategies would likely be preferred to tease out the existence of the  $H^\pm$ . However, such top partners would at least be discovered via the kinds of multi- $b$  searches used to hunt for  $T \rightarrow th$  final states, as long as no  $m_{bb} = m_h$  requirement is applied.

Efficiencies for passing the given selection criteria, and corresponding values of  $\epsilon$  yielding  $2\sigma$  and  $5\sigma$  significances with the branching ratios described above, are given in Table 2 for several representative values of  $m_{H^\pm}$ . For  $m_{H^\pm} \approx m_T$ , the efficiency for the signal process to pass the selection criteria falls because the  $b$  quark from  $T \rightarrow bH^\pm$  becomes softer, increasing the likelihood of an event failing cut 6 by having  $\min(m_{bb}) < 150$  GeV. Thus, in these regions of parameter space, a larger  $T \rightarrow bH^\pm$  branching ratio is required for this to be a viable search strategy – unfortunately, also in these regions, the phase space suppression of  $T \rightarrow bH^\pm$  will be greater, likely reducing this branching ratio. For optimal coverage of this squeezed region, it might be worth pursuing a set of dedicated cuts. For larger values of  $m_T$ , we anticipate that comparable separation from SM backgrounds could be achieved with slightly looser cuts due to the increased hardness of the event. The corresponding increase in efficiency could partially mitigate the rapid decrease in  $\sigma_{\text{NLO}}(pp \rightarrow TT)$  with  $m_T$  (Fig. 3).

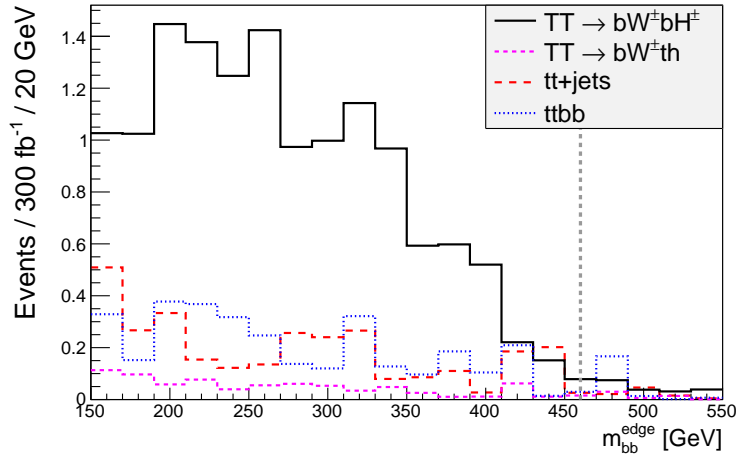
To demonstrate the potential reach of this search at the LHC with very high luminosity, we present the analog of Table 2 for  $m_T = 1$  TeV and  $\mathcal{L} = 3000 \text{ fb}^{-1}$  in Table 3. The increase in luminosity is necessary to compensate for the decrease in production cross section,

$$\sigma_{\text{incl}}(pp \rightarrow TT, m_T = 1 \text{ TeV}) = 60 \text{ fb}. \quad (3.16)$$

In this case, we modify cuts 7 and 8 to require  $m_{b_1jj} \in [900, 1050]$  GeV and  $m_{b_2b_3b_4\ell\bar{\ell}E_T} \in [800, 1100]$  GeV. Ideally, however, the other cuts would also be optimized for  $m_T = 1$  TeV. For instance, heavier top partners produce events with larger  $p_{T,b_1}$  and  $m_{\text{eff}}$ , such that harsher

$m_T$	$m_{H^\pm}$	Efficiency	Events [ $\mathcal{L} = 3000 \text{ fb}^{-1}$ ]	$\epsilon (2\sigma)$	$\epsilon (5\sigma)$
	400	$1.2 \times 10^{-3}$	110 $\text{Br}_{bWbH^\pm}$	0.07	0.19
1000	600	$1.7 \times 10^{-3}$	150 $\text{Br}_{bWbH^\pm}$	0.05	0.13
	800	$1.4 \times 10^{-3}$	120 $\text{Br}_{bWbH^\pm}$	0.06	0.17

**Table 3:** Efficiencies for passing the given selection criteria for  $m_T = 1 \text{ TeV}$  and several representative values of  $m_{H^\pm}$ . Also shown are corresponding values of  $\epsilon$  (defined in Eq. (3.14)) yielding  $2\sigma$  and  $5\sigma$  significance assuming  $\text{Br}(H^\pm \rightarrow tb) = 1$  and  $\mathcal{L} = 3000 \text{ fb}^{-1}$ . In this case, we require  $m_{b_{1jj}} \in [900, 1050] \text{ GeV}$  and  $m_{b_2b_3b_4\cancel{E}_T} \in [800, 1100] \text{ GeV}$ . For these cuts, the  $tt+\text{jets}$  and  $t\bar{t}bb$  SM processes contribute 6.9 and 3.9 background events, respectively. The  $2\sigma$  ( $5\sigma$ ) significances correspond to  $S \approx 7.0$  (17.2) and  $B \approx 11.8$  (11.6).



**Figure 6:** Distribution of  $m_{bb}^{\text{edge}}$  taking  $m_T = 700 \text{ GeV}$ ,  $m_{H^\pm} = 500 \text{ GeV}$ ,  $\epsilon = 0.12$ . The  $TT \rightarrow bW^\pm tZ$  distribution is not shown as it is similar in shape to the  $TT \rightarrow bW^\pm th$  distribution, but is suppressed as  $\text{Br}(Z \rightarrow bb) < \text{Br}(h \rightarrow bb)$ . For these values, the  $b$ 's from  $T \rightarrow H^\pm b \rightarrow tbb$  are constrained to have  $m_{bb}^{\text{edge}} \leq 460 \text{ GeV}$  (dashed line, see Eq. (3.17)).

basic cuts may be preferred to further suppress SM backgrounds. As the  $W^\pm$  from the  $T \rightarrow bW_{\text{had}}^\pm$  decay would be more boosted, cut 7 could also be modified to require more collimated jets—jet substructure techniques may even prove useful in this regime. Finally, as heavier top partners permit more phase space for decays, the  $\min(m_{bb})$  required could conceivably be increased. Appropriately optimizing cuts for different candidate values of  $m_T$  would extend the reach of this search.

The above analysis strategy was aimed at getting a signal to background ratio of  $\mathcal{O}(1)$ , so relatively harsh cuts were needed to control the SM background from top quarks. One drawback of this analysis strategy is that the number of signal events passing these criteria is likely to be small, precluding the observation of, e.g., a resonance peak at  $m_{tb} = m_{H^\pm}$ .

$m_T$	$m_{\varphi^0}$	Efficiency	Events [300 fb <sup>-1</sup> ]	$\epsilon$ (2 $\sigma$ )	$\epsilon$ (5 $\sigma$ )
700	350	$1.3 \times 10^{-3}$	120 Br <sub><math>bWt\varphi^0</math></sub>	0.05	0.13
	450	$9.9 \times 10^{-4}$	88 Br <sub><math>bWt\varphi^0</math></sub>	0.07	0.19

**Table 4:** Efficiencies for passing the given selection criteria for several representative values of  $m_{\varphi^0}$ . Also shown are corresponding values of  $\epsilon$  yielding 2 $\sigma$  and 5 $\sigma$  significance assuming  $\text{Br}(\varphi^0 \rightarrow bb) = 1$ . As in Table 2, 2 $\sigma$  (5 $\sigma$ ) significances correspond to  $S \approx 5.5$  (13.7) and  $B \approx 7.7$  (7.5).

Multivariate techniques may extend the discovery potential of this search, but are unlikely to increase event yields sufficiently to allow for the determination of  $m_{H^\pm}$  unless looser event selection criteria (and alternative ways of controlling the SM top backgrounds) are used. However, with sufficient data, there are numerous methods through which the charged Higgs mass could be extracted from this channel, even if  $H^\pm$  has leptonic decays. For example, one way to access the  $H^\pm$  mass is via the edge in the  $m_{bb}$  distribution for the  $b$ 's produced in the decay  $T \rightarrow H^\pm b \rightarrow tbb$ ,

$$m_{bb} \leq m_T \sqrt{1 - \frac{m_{H^\pm}^2}{m_T^2}} \sqrt{1 - \frac{m_t^2}{m_{H^\pm}^2}}. \quad (3.17)$$

This, too is likely to be challenging due to small statistics, but given lighter top partners, a sufficiently large data set, or generous branching ratios, it could be worth pursuing further. To give an idea of how this might work, we first attempt to identify the  $b$  quark coming from the top decay by minimizing  $|m_{b_k \ell \cancel{E}_T} - m_t|$  ( $k = 2, 3, 4$ , i.e. excluding the harder  $b$  used in the other side  $T$  reconstruction). We denote this  $b$  as  $b_t$ . We can then examine the invariant mass distribution of the remaining two  $b$  quarks:  $m_{bb}^{\text{edge}}$ . A sample distribution is shown for  $m_T = 700$  GeV,  $m_{H^\pm} = 500$  GeV, and  $\epsilon = 0.12$  in Fig. 6. For these values,  $m_{bb}^{\text{edge}} \leq 460$  GeV. Unlike attempting to observe a resonance in an  $m_{tb}$  distribution, the  $m_{bb}^{\text{edge}}$  distribution has the advantage of not being subject to combinatoric ambiguity once  $m_{b_t \ell \cancel{E}_T} \approx m_t$  has been used to identify the bottom arising from the leptonic top quark decay.

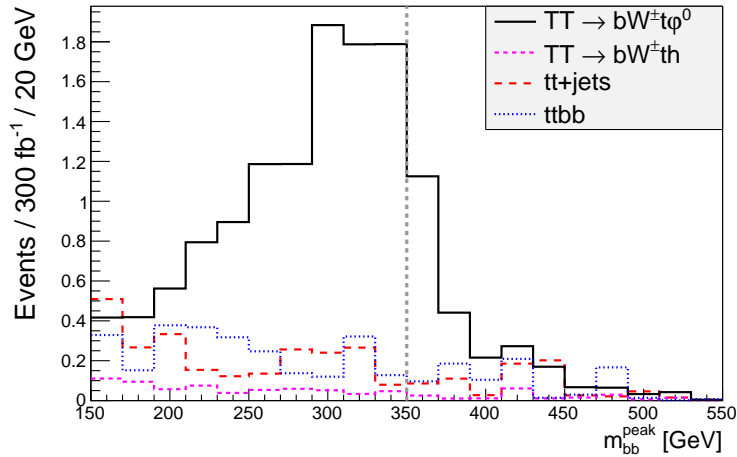
## 4 Applicability to Neutral Scalars

The strategy outlined above is clearly suitable for searching for any charged scalars  $\varphi^\pm$  produced in top partner decays  $T \rightarrow b\varphi^\pm$  with  $\varphi^\pm \rightarrow tb$ . However, it is also applicable to heavier neutral scalar states  $\varphi^0$  produced via  $T \rightarrow t\varphi^0$  and decaying as  $\varphi^0 \rightarrow bb$ ,

$$pp \rightarrow (T \rightarrow bW_{\text{had}}^\pm)(T \rightarrow t\varphi^0 \rightarrow t_{\text{lep}}bb) \rightarrow 4b + 2j + \ell\nu. \quad (4.1)$$

While one could imagine other dedicated searches for such a  $\varphi^0$ , the search strategy provided already for  $H^\pm$  would at least uncover an excess as long as  $m_{\varphi^0} > 150$  GeV to satisfy the conditions of cut 6.

Efficiencies for two sample values of  $m_{\varphi^0}$  are given in Table 4, along with corresponding values of  $\epsilon$  yielding 2 $\sigma$  and 5 $\sigma$  significances (as above, taking  $\text{Br}(T \rightarrow t\varphi^0) = \epsilon$  and  $\text{Br}(T \rightarrow$



**Figure 7:** Distribution of  $m_{bb}^{\text{peak}}$  taking  $m_T = 700$  GeV,  $m_{\varphi^0} = 350$  GeV,  $\epsilon = 0.13$ . We assume  $\text{Br}(\varphi^0 \rightarrow bb) = 1$ . In contrast to Fig. 6, this  $b$  pair should reconstruct the  $\varphi^0$ , producing a resonance peak at  $m_{\varphi^0}$  (dashed line).

$bW^\pm : th : tZ = (1 - \epsilon) \times (\frac{1}{2} : \frac{1}{4} : \frac{1}{4})$ . As expected, the efficiencies and branching ratios reach are comparable to the  $T \rightarrow bH^\pm$  search.

Of course, the  $bb$  pair produced in  $T \rightarrow t\varphi^0 \rightarrow tbb$  should exhibit a resonance structure at  $m_{bb} = m_{\varphi^0}$ , so by employing a similar tactic to that used above to identify the edge (i.e. by forming  $m_{bb}^{\text{peak}}$  using the pair of  $b$ 's in  $\{b_2, b_3, b_4\}$  that do not give the minimum  $|m_{b_k \ell \cancel{E}_T} - m_t|$ ) one could attempt to search for a resonance peak. A sample distribution for  $m_T = 700$  GeV,  $m_{\varphi^0} = 350$  GeV, and  $\epsilon = 0.13$  is shown in Fig. 7. The resonance peak is not particularly sharp in part because we are not using the full neutrino four-momentum to reject the  $b$  jet from the top decay and mitigate combinatoric confusion. The peak could potentially be improved by solving for the full four-momentum with  $p_T^\nu = \cancel{p}_T$  and requiring  $m_{\ell\nu} = m_W$  and  $m_{bb\ell\nu} = m_T$ . Again, the feasibility of discovering a resonance structure in this fashion is limited due to the small statistics, but such a structure could in principle help not only to determine  $m_{\varphi^0}$  but also to distinguish between  $T \rightarrow bH^\pm$  and  $T \rightarrow t\varphi^0$ .

## 5 Conclusions

If the weak scale is in fact natural, new states should soon be discovered at the LHC. These new states would of course provide insights into why the Higgs boson has a weak scale mass, but they might also provide an unexpected window into a rich scalar sector that would be otherwise difficult to access experimentally. In this paper, we have argued that heavy charged Higgs bosons can be challenging to observe in standard channels, but they might well be discoverable in the decays of top partners. Top partner decays can also be sensitive to exotic neutral scalars.

We have focused on methods for observing extended Higgs sector scalars that decay predominantly via  $H^\pm \rightarrow tb$  or  $\varphi^0 \rightarrow bb$ . These decay channels are likely to dominate if the extended Higgs sector scalars have large couplings to third-generation quarks. That said, other decay modes may also be present depending on the exact structure of the theory. For instance, decays like  $H^\pm \rightarrow \tau^\pm \nu_\tau$  or  $H^\pm \rightarrow W^\pm h$  may provide alternative signatures of scalars produced either directly or in fermionic top partner decays.

The strategy presented here makes use of the (likely significant)  $T \rightarrow bW^\pm$  decay to tag top partner pair production events. However, if other top partner decay modes dominate, alternative search strategies would be preferred. In particular, if the top partner decays predominantly as  $T \rightarrow th$ , a cut on  $\min(m_{bb})$  can no longer be employed to separate signal from background. The decay  $TT \rightarrow thbH^\pm$  would yield a striking  $6b, 2W^\pm$  final state, but combinatoric backgrounds associated with the large number of  $b$ -jets would make it difficult to disentangle this decay pattern from, e.g.,  $TT \rightarrow thth$ . Similarly, bottom partners  $B$  are also expected to be light if they are in an electroweak doublet with the top partner  $T$ , and the decay mode  $BB \rightarrow tW^\pm tH^\pm$  ( $BB \rightarrow bhtH^\pm$ ) yields a striking  $4b, 4W^\pm$  ( $6b, 2W^\pm$ ) final state, albeit with significant combinatoric confusion.

Finally, while this search strategy could reveal the presence of extended Higgs sector scalars, distinguishing between  $T \rightarrow t\varphi^0 \rightarrow tbb$  and  $T \rightarrow H^\pm b \rightarrow tbb$  would likely prove challenging given the small statistics. Of course, the first priority is to determine the presence of additional scalar states, but how to determine their properties is a question of great interest, especially given the difficulty in uncovering them in the first place. We leave these questions for future investigation, as we await hints of naturalness from the LHC.

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## References

- [1] A. Datta, A. Djouadi, M. Guchait, and Y. Mambrini, *Charged Higgs production from SUSY particle cascade decays at the CERN LHC*, *Phys.Rev.* **D65** (2002) 015007, [[hep-ph/0107271](#)].
- [2] A. Datta, A. Djouadi, M. Guchait, and F. Moortgat, *Detection of mssm higgs bosons from supersymmetric particle cascade decays at the LHC*, *Nucl.Phys.* **B681** (2004) 31–64, [[hep-ph/0303095](#)].
- [3] G. D. Kribs, A. Martin, and T. S. Roy, *Higgs boson discovery through top-partners decays using jet substructure*, *Phys.Rev.* **D84** (2011) 095024, [[arXiv:1012.2866](#)].

- [4] V. D. Barger, R. Phillips, and D. Roy, *Heavy charged Higgs signals at the LHC*, *Phys.Lett.* **B324** (1994) 236–240, [[hep-ph/9311372](#)].
- [5] J. Gunion, *Detecting the  $t b$  decays of a charged Higgs boson at a hadron supercollider*, *Phys.Lett.* **B322** (1994) 125–130, [[hep-ph/9312201](#)].
- [6] N. Arkani-Hamed, A. G. Cohen, and H. Georgi, *Electroweak symmetry breaking from dimensional deconstruction*, *Phys.Lett.* **B513** (2001) 232–240, [[hep-ph/0105239](#)].
- [7] N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson, T. Gregoire, et al., *The Minimal moose for a little Higgs*, *JHEP* **0208** (2002) 021, [[hep-ph/0206020](#)].
- [8] N. Arkani-Hamed, A. Cohen, E. Katz, and A. Nelson, *The Littlest Higgs*, *JHEP* **0207** (2002) 034, [[hep-ph/0206021](#)].
- [9] M. Schmaltz and D. Tucker-Smith, *Little Higgs review*, *Ann.Rev.Nucl.Part.Sci.* **55** (2005) 229–270, [[hep-ph/0502182](#)].
- [10] M. Perelstein, *Little Higgs models and their phenomenology*, *Prog.Part.Nucl.Phys.* **58** (2007) 247–291, [[hep-ph/0512128](#)].
- [11] J. Kearney, A. Pierce, and J. Thaler, *Exotic Top Partners and Little Higgs*, [arXiv:1306.4314](#).
- [12] S. Chang and J. G. Wacker, *Little Higgs and custodial  $SU(2)$* , *Phys.Rev.* **D69** (2004) 035002, [[hep-ph/0303001](#)].
- [13] S. Chang, *A ‘Littlest Higgs’ model with custodial  $SU(2)$  symmetry*, *JHEP* **0312** (2003) 057, [[hep-ph/0306034](#)].
- [14] K. Agashe, R. Contino, L. Da Rold, and A. Pomarol, *A Custodial symmetry for  $Zb$  anti- $b$* , *Phys.Lett.* **B641** (2006) 62–66, [[hep-ph/0605341](#)].
- [15] E. Katz, J.-y. Lee, A. E. Nelson, and D. G. Walker, *A Composite little Higgs model*, *JHEP* **0510** (2005) 088, [[hep-ph/0312287](#)].
- [16] J. Thaler and I. Yavin, *The Littlest Higgs in Anti-de Sitter space*, *JHEP* **0508** (2005) 022, [[hep-ph/0501036](#)].
- [17] M. Schmaltz and J. Thaler, *Collective Quartics and Dangerous Singlets in Little Higgs*, *JHEP* **0903** (2009) 137, [[arXiv:0812.2477](#)].
- [18] H.-C. Cheng and I. Low, *TeV symmetry and the little hierarchy problem*, *JHEP* **0309** (2003) 051, [[hep-ph/0308199](#)].
- [19] H.-C. Cheng and I. Low, *Little hierarchy, little Higgses, and a little symmetry*, *JHEP* **0408** (2004) 061, [[hep-ph/0405243](#)].
- [20] S. Bar-Shalom, M. Geller, S. Nandi, and A. Soni, *Two Higgs doublets, a 4th generation and a 125 GeV Higgs*, [arXiv:1208.3195](#).
- [21] M. Geller, S. Bar-Shalom, G. Eilam, and A. Soni, *The 125 GeV Higgs in the context of four generations with 2 Higgs doublets*, *Phys.Rev.* **D86** (2012) 115008, [[arXiv:1209.4081](#)].
- [22] O. Deschamps, S. Descotes-Genon, S. Monteil, V. Niess, S. T’Jampens, et al., *The Two Higgs Doublet of Type II facing flavour physics data*, *Phys.Rev.* **D82** (2010) 073012, [[arXiv:0907.5135](#)].

- [23] C.-Y. Chen and S. Dawson, *Exploring Two Higgs Doublet Models Through Higgs Production*, [arXiv:1301.0309](#).
- [24] S. Moretti and D. Roy, *Detecting heavy charged Higgs bosons at the LHC with triple b tagging*, *Phys.Lett.* **B470** (1999) 209–214, [[hep-ph/9909435](#)].
- [25] K. Assamagan, *The charged Higgs in hadronic decays with the ATLAS detector*, *Acta Phys.Polon.* **B31** (2000) 863–879.
- [26] **ATLAS Collaboration** Collaboration, *Calibrating the b-Tag Efficiency and Mistag Rate in  $35\text{pb}^{-1}$  of Data with the ATLAS Detector*, .
- [27] **ATLAS Collaboration** Collaboration, *ATLAS: Detector and physics performance technical design report. Volume 1*, .
- [28] D. Miller, S. Moretti, D. Roy, and W. J. Stirling, *Detecting heavy charged Higgs bosons at the CERN LHC with four b quark tags*, *Phys.Rev.* **D61** (2000) 055011, [[hep-ph/9906230](#)].
- [29] K. A. Assamagan and N. Gollub, *The ATLAS discovery potential for a heavy charged Higgs boson in  $gg \rightarrow tbH^\pm$  with  $H^\pm \rightarrow tb$* , *Eur.Phys.J.* **C39S2** (2005) 25–40, [[hep-ph/0406013](#)].
- [30] **LHC Higgs Cross Section Working Group** Collaboration, S. Dittmaier et al., *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, [arXiv:1101.0593](#).
- [31] S. Yang and Q.-S. Yan, *Searching for Heavy Charged Higgs Boson with Jet Substructure at the LHC*, *JHEP* **1202** (2012) 074, [[arXiv:1111.4530](#)].
- [32] T. Han, H. E. Logan, B. McElrath, and L.-T. Wang, *Phenomenology of the little Higgs model*, *Phys.Rev.* **D67** (2003) 095004, [[hep-ph/0301040](#)].
- [33] M. Perelstein, M. E. Peskin, and A. Pierce, *Top quarks and electroweak symmetry breaking in little Higgs models*, *Phys.Rev.* **D69** (2004) 075002, [[hep-ph/0310039](#)].
- [34] Y. Okada and L. Panizzi, *LHC signatures of vector-like quarks*, [arXiv:1207.5607](#).
- [35] A. De Simone, O. Matsedonskyi, R. Rattazzi, and A. Wulzer, *A First Top Partner’s Hunter Guide*, *JHEP* **1304** (2013) 004, [[arXiv:1211.5663](#)].
- [36] **ATLAS Collaboration** Collaboration, G. Aad et al., *Search for pair production of heavy top-like quarks decaying to a high- $p_T$   $W$  boson and a  $b$  quark in the lepton plus jets final state at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *Phys.Lett.* **B718** (2013) 1284–1302, [[arXiv:1210.5468](#)].
- [37] **CMS Collaboration** Collaboration, S. Chatrchyan et al., *Search for pair produced fourth-generation up-type quarks in  $pp$  collisions at  $\sqrt{s} = 7$  TeV with a lepton in the final state*, *Phys.Lett.* **B718** (2012) 307–328, [[arXiv:1209.0471](#)].
- [38] D. Berenstein, T. Liu, and E. Perkins, *Multiple b-jets reveal natural SUSY and the 125 GeV Higgs*, [arXiv:1211.4288](#).
- [39] K. Harigaya, S. Matsumoto, M. M. Nojiri, and K. Tobioka, *Search for the Top Partner at the LHC using Multi-b-Jet Channels*, *Phys.Rev.* **D86** (2012) 015005, [[arXiv:1204.2317](#)].
- [40] K. Rao and D. Whiteson, *Triangulating an exotic  $T$  quark*, *Phys.Rev.* **D86** (2012) 015008, [[arXiv:1204.4504](#)].
- [41] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **1106** (2011) 128, [[arXiv:1106.0522](#)].

- [42] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **0605** (2006) 026, [[hep-ph/0603175](#)].
- [43] M. L. Mangano, M. Moretti, F. Piccinini, and M. Treccani, *Matching matrix elements and shower evolution for top-quark production in hadronic collisions*, *JHEP* **0701** (2007) 013, [[hep-ph/0611129](#)].
- [44] S. Mrenna and P. Richardson, *Matching matrix elements and parton showers with HERWIG and PYTHIA*, *JHEP* **0405** (2004) 040, [[hep-ph/0312274](#)].
- [45] M. Aliev, H. Lacker, U. Langenfeld, S. Moch, P. Uwer, et al., *HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR*, *Comput.Phys.Commun.* **182** (2011) 1034–1046, [[arXiv:1007.1327](#)].
- [46] S. Ovin, X. Rouby, and V. Lemaitre, *DELPHES, a framework for fast simulation of a generic collider experiment*, [arXiv:0903.2225](#).
- [47] J. de Favereau, X. Rouby, and K. Piotrkowski, *Hector: A Fast simulator for the transport of particles in beamlines*, *JINST* **2** (2007) P09005, [[arXiv:0707.1198](#)].
- [48] L. Quertenmont and V. Roberfroid, *FROG: The Fast & Realistic OPENGL Displayer*, [arXiv:0901.2718](#).
- [49] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet User Manual*, *Eur.Phys.J.* **C72** (2012) 1896, [[arXiv:1111.6097](#)].
- [50] R. Brun and F. Rademakers, *ROOT: An object oriented data analysis framework*, *Nucl.Instrum.Meth.* **A389** (1997) 81–86.
- [51] M. Cacciari, G. P. Salam, and G. Soyez, *The Anti- $k(t)$  jet clustering algorithm*, *JHEP* **0804** (2008) 063, [[arXiv:0802.1189](#)].
- [52] **ATLAS Collaboration** Collaboration, G. Aad et al., *Measurement of the top quark pair production cross-section with ATLAS in the single lepton channel*, *Phys.Lett.* **B711** (2012) 244–263, [[arXiv:1201.1889](#)].
- [53] J. M. Cornwall, D. N. Levin, and G. Tiktopoulos, *Derivation of Gauge Invariance from High-Energy Unitarity Bounds on the  $s$  Matrix*, *Phys.Rev.* **D10** (1974) 1145.
- [54] C. Vayonakis, *Born Helicity Amplitudes and Cross-Sections in Nonabelian Gauge Theories*, *Lett.Nuovo Cim.* **17** (1976) 383.
- [55] B. W. Lee, C. Quigg, and H. Thacker, *Weak Interactions at Very High-Energies: The Role of the Higgs Boson Mass*, *Phys.Rev.* **D16** (1977) 1519.
- [56] M. Schmaltz, D. Stolarski, and J. Thaler, *The Bestest Little Higgs*, *JHEP* **1009** (2010) 018, [[arXiv:1006.1356](#)].
- [57] S. Godfrey, T. Gregoire, P. Kalyniak, T. A. Martin, and K. Moats, *Exploring the heavy quark sector of the Bestest Little Higgs model at the LHC*, *JHEP* **1204** (2012) 032, [[arXiv:1201.1951](#)].