Heavy Higgs Bosons at Low $\tan \beta$:
from the LHC to 100 TeV

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ABSTRACT: We present strategies to search for heavy neutral Higgs bosons decaying to top quark pairs, as often occurs at low $\tan \beta$ in type II two Higgs doublet models such as the Higgs sector of the MSSM. The resonant production channel is unsatisfactory due to interference with the SM background. We instead propose to utilize same-sign dilepton signatures arising from the production of heavy Higgs bosons in association with one or two top quarks and subsequent decay to a top pair. We find that for heavier neutral Higgs bosons the production in association with one top quark provides greater sensitivity than production in association with two top quarks. We obtain current limits at the LHC using Run I data at 8 TeV and forecast the sensitivity of a dedicated analysis during Run II at 14 TeV. Then we perform a detailed BDT study for the 14 TeV LHC and a future 100 TeV collider.

https://github.com/BoostedColliderAnalysis/BoCA

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1 Introduction

The search for additional Higgs bosons is a high priority for current and future colliders. The ATLAS and CMS collaborations have performed searches for heavy neutral [1–9] and charged [10–12] Higgs bosons during the first run of the Large Hadron Collider (LHC) at $\sqrt{s} = 8$ TeV. The reach of such searches will expand considerably in the future; in its second run, the LHC has started to take data at $\sqrt{s} = 13$ TeV, with an eventual goal of collisions at $\sqrt{s} = 14$ TeV. In the long run, the center-of-mass energy of next-generation pp-colliders can be as much as an order of magnitude higher than that of the LHC. Such a high energy scale opens up new signal channels which are suppressed at lower energies.

Among the most challenging scenarios are those in which heavy neutral Higgs bosons decay predominantly into $t\bar{t}$ pairs. Dedicated studies probing the heavy Higgs sector via $t\bar{t}$ final states have recently been presented for the LHC [13–17] and a 100 TeV collider [15]. In motivated models for extended Higgs sectors described by a type II two Higgs doublet model (2HDM), the moderate tan $\beta$ region can be covered up to 1 TeV using BDT methods, in large part by using bottom quark associated production. However, the low tan $\beta$ region remains thus far uncovered as the conventional resonant $t\bar{t}$ channel suffers from interference with
the Standard Model background [18–21] and the cross section for bottom quark associated production is negligible. This motivates dedicated searches for signals in the low $\tan\beta$ region; the development of strategies for such searches is the goal of this paper.

Given that gluon fusion and bottom quark associated production modes are unpromising, we propose to cover the low $\tan\beta$ region through top associated production modes, namely

Figure 1: (a) Distribution of the rapidity difference between two bottom quarks at 14 TeV for a 500 GeV heavy Higgs. The rapidity difference is calculated between the bottom pair found in the decay products of the particles produced in association with the heavy Higgs, which involves either one (red) or two (black) top quarks. (b) Distribution of the rapidity difference at 100 TeV for a 5 TeV heavy Higgs. For comparison, in each case we also show the maximal rapidity difference between all $b$-quarks in the $ttt\bar{t}$ background (green), as well as between the soft additional $b$ and one of the $b$-quarks coming from a top decay in the $ttW^\pm b$ background (blue). Additionally, we show the rapidity difference between the two $b$ quarks in the $ttW^\pm\bar{b}b$ background (pink).

Figure 2: (a) Transverse momenta of the leptons at 14 TeV for a 500 GeV heavy Higgs. The transverse momenta are plotted for the two signal channels $H/At\bar{t}$ (black) and $H/AW^\pm tb$ (red) for cases in which the lepton comes from the decay products of a heavy Higgs boson (dotted) or the decay products of an associated particle ($W$ boson for three-top case) (solid). (b) Transverse momenta of the leptons at 100 TeV for a 5 TeV heavy Higgs.
the channels

- \( pp \rightarrow t\bar{t}H \rightarrow t\bar{t}t\bar{t} \),
- \( pp \rightarrow iHW^+b \rightarrow t\bar{t}W^+b \) and \( pp \rightarrow tHW^-\bar{b} \rightarrow t\bar{t}W^-\bar{b} \).\(^1\)

These channels are ideally suited for probing the low \( \tan \beta \) region, since they do not suffer significant interference with Standard Model backgrounds, and the corresponding production cross sections are maximized for low \( \tan \beta \) in type II 2HDM. Various aspects of these channels have already been discussed \([22–25]\). In this work we develop an optimized strategy for probing extended Higgs sectors in top associated production by focusing on the three main kinematic features of these channels: First, large heavy Higgs masses lead to a sizable scalar sum of transverse momenta \( H_T \). Second, we use the forward-/backwardness of the accompanying quarks. Although the heavy Higgs is produced in association with one or two top quarks, the bottom quarks resulting from heavy Higgs decays still tend to be forward/backward, as shown in Figure 1. This feature discriminates against backgrounds other than the irreducible \( t\bar{t}t\bar{t} \) background. Third, we make use of the same-sign di-lepton (SSDL) signature present in these signal channels. Especially in the \( pp \rightarrow iHW^+b \) channel, the transverse momentum of the lepton originating from the decay of the associated W boson is comparable to the one originating from the decay of the heavy Higgs, as shown in Figure 2.

The paper is organized as follows: In Section 2, we study general features of heavy Higgs associated production at the Large Hadron Collider and a future \( pp \)-collider operating at \( \sqrt{s} = 100 \) TeV. We then consider constraints from existing SSDL searches at the 8 TeV LHC in Section 3 in a simplified model framework with a single scalar or pseudoscalar heavy Higgs. We then turn to prospects for probing both scalar and pseudoscalar heavy Higgses in type II 2HDM at present and future colliders. We discuss the relevant backgrounds and introduce our analysis strategies in Section 4. We present the results of these analyses in Section 5 and we summarize our work in Section 6. We reserve details of the BDT used in our 14 TeV and 100 TeV analyses for Appendix A, and a discussion of the related \( bb \) associated production channel for Appendix B.

2 The Higgs Sector

For the sake of concreteness, in this work we will focus on extended Higgs sectors whose low-energy physics can be characterized by a two Higgs doublet model of type II, such as the Higgs sector of the MSSM. In addition to the SM-like Higgs boson, these sectors contain two heavy neutral Higgs bosons — one CP-even \( (H) \) and one CP-odd \( (A) \) — and a pair of charged Higgs bosons \( (H^\pm) \). The physics of these bosons is governed at tree level by a neutral mixing angle and the ratio of the Higgs vacuum expectation values \( \tan \beta \). In the particular case of the MSSM, the neutral mixing angle is further fixed by the mass scale of the heavy Higgs bosons. Current Higgs coupling measurements require such extended

\(^1\)Whenever we will mention in the following just one of these two conjugated processes, we implicitly mean both \( pp \rightarrow iHW^+b \) and \( pp \rightarrow tHW^-\bar{b} \), together.
Higgs sectors to be near an alignment limit of the parameter space [26–30], in which the couplings of the light CP-even Higgs scalar are Standard Model-like.

2.1 Production of heavy scalars in association with top quark(s)

The physics of the alignment limit provides a natural organizing principle for associated production modes of the heavy Higgs bosons. In the alignment limit with small $\tan \beta$, the $HW^+W^-$ and $bbH(A)$ couplings are suppressed, so that the dominant contributions to $H(A)$ production arise from the $ttH(A)$ vertex. This leads to a variety of production processes in association with $tt$ pairs that can be generated from the standard model (SM) top production processes with an additional heavy scalar radiated from the internal top quark (Figure 3a) or an external top quark leg (Figure 3b and 3c).

Figure 3: Typical Feynman diagrams for the production of a heavy scalar in association with a top pair at proton-proton colliders.

In addition to production of a heavy Higgs in association with top quark pairs, production in association with a single top quark may play a useful role. Production of Higgs bosons in association with single top quarks was studied extensively in [31, 32], although the details differ somewhat near the alignment limit where radiation of heavy Higgses from vector bosons is suppressed. The production of a heavy scalar in association with a single top quark in the alignment limit contains three main channels: $t$-channel (Figure 4a), $s$-channel (Figure 4b) and $tW$-associated production channel (Figure 4c and 4d). The $s$-channel process is highly suppressed by the center of mass energy $1/s^2$ and is much smaller than the other two. Although the $t$-channel process is suppressed by a factor of $\alpha/ (\alpha_s \sin^2 \theta_W)$, its cross-section is larger than that of the $tW$-associated channel on account of the larger phase space and the parton distribution function (PDF) of the valence quark. However, as shown in Figure 4, the cross-section of the $tW$-associated channel for the heavy scalar

Figure 4: Typical Feynman diagrams for the production of a heavy scalar in association with a single top quark at proton-proton colliders.
with single top production is increased by the additional possibility of internal radiation. Furthermore, the suppression from the phase space volume is no longer significant when the scalar is heavy, because the volume of phase space is determined by the mass of the heavy scalar. Thus both the $t$-channel and $tW$-associated channels contribute significantly to the total cross section for production of a heavy Higgs boson in association with a single top quark.

Although a variety of search strategies are sensitive to this final state, in this work we focus on final states involving same-sign dileptons. If we require the signal events to contain SSDL, the contribution from the $tWH(A)$ channel will be enhanced by the possibility of the charged lepton from the $W^\pm$ decay. Hence we expect the dominant contributions from new physics in SSDL final states to come from the $tWH(A)$ channel, with a sub-dominant contribution coming from the $tqH(A)$ channel. The $s$-channel contribution should be negligibly small as discussed above.

In comparison, the rate for $t\bar{t}H(A)$ production is only slightly suppressed by the phase space, and is enhanced relative to single-top processes by both the coupling constant of the strong interaction $\mathcal{O}(\alpha_s \sin^2 \theta_W/\alpha)$ and the gluon PDF. Hence the contributions from $t\bar{t}$ associated production are expected to be significant, especially when searching for SSDL signals. In this work we consider both single-top and $t\bar{t}$ associated production processes.

In what follows, we will both obtain existing limits on these processes by reinterpreting SSDL searches at $\sqrt{s} = 8$ TeV and forecast the reach of the $\sqrt{s} = 14$ TeV LHC and future $pp$-collider in SSDL channels. To do so, we work in terms of a simplified model in which $H(A)$ couples to the SM particles via

$$\mathcal{L} = -y_t(c_H H\bar{t}t + ic_A A\bar{t}\gamma_5 t),$$

where $y_t$, $y_b$ and $y_\tau$ are the SM Yukawa coupling constant of the third generation leptons. As we are focusing on the case with small $\tan \beta$ we will neglect the sub-dominant coupling to $b$ and $\tau$ when we derive limits on the coefficients $c_H, c_A$.

We calculate the leading order (LO) cross-sections using MadGraph 5 [33] with CT14lo PDF in the 5-flavor scheme (FS) [34]. For the $tH(A) + X$ processes, we choose the factorization and renormalization scales to be $\mu_F = \mu_R = m_t^{\overline{MS}} + m_{H(A)}^\text{MS}$, where $m_t^{\overline{MS}} = 163$ GeV is the MS mass of the SM top quark. For $t\bar{t}H(A)$ process, we instead choose $\mu_F = \mu_R = m_t^{\overline{MS}} + m_{H(A)}/2$. The resulting cross sections for the $8$ TeV and $14$ TeV LHC are shown in Figure 5. Notice that the 4-top process has larger scale uncertainty since it is $\mathcal{O}\left(\alpha_s^2\right)$, while the 3-top processes are $\mathcal{O}(\alpha_s)$.

For the $14$ TeV LHC and a future $100$ TeV $pp$-collider we present additionally the contours in the $m_A$-$\tan \beta$ plane for the production cross-sections of the $pp \to t\bar{t}H(A)$ and the $pp \to tWH(A)$ processes within the framework of the MSSM in Figure 6. We point out that for low masses the cross-section of the $tWH(A)$ processes is smaller than that of $t\bar{t}H(A)$ processes, but that the situation reverses at large heavy Higgs masses due to the asymptotic freedom of $\alpha_s$ together with the faster falloff in $x$ of the gluon PDF relative to the bottom-quark PDF.
Figure 5: (a) Cross-sections of the 3-top (colored) and 4-top (black) processes for a CP-even heavy Higgs at the 8 TeV LHC, where the number of top quarks includes both the associated states and the $t\bar{t}$ decay of the heavy Higgs. (b) The corresponding cross sections for a CP-odd heavy Higgs. (c) Cross-sections of the 3-top (colored) and 4-top (black) processes for a CP-even heavy Higgs at the 14 TeV. (d) The corresponding cross sections for a CP-odd heavy Higgs. In each case the shaded regions represent the scale uncertainties. Note the difference of uncertainties for processes proportional to $\alpha_s$ and $\alpha_s^2$. In simulating these cross-sections we have assumed that the heavy Higgs coupling to bottom quarks and $\tau$-lepton are negligible, which corresponds to small values of $\tan\beta$.

3 Constraint from LHC Run I

Before developing a strategy for future searches, it is useful to determine the state of existing limits from searches at the 8 TeV LHC. In this section, we find the constraint on heavy Higgs bosons coming from an SSDL search performed by the CMS collaboration [35]. We consider a simplified model containing a heavy scalar or pseudoscalar Higgs boson with coupling to the top quark as in Equation (2.1). The three-top signal events are generated to leading order (LO) at parton level with CTEQ6L1 PDFs [36] within the 5-flavor scheme using MadGraph [33]. The renormalization and factorization scales are set to
be $\mu_R = \mu_F = m_t + m_{H(A)}$. We also generate four-top signal events with the same method as the three-top signal events. The renormalization and factorization scales for four-top processes are set to be $\mu_R = \mu_F = m_t + m_{H(A)}/2$.

In both cases, the top quarks in the final state are decayed using MadGraph in order to preserve the effects of spin correlations. Events are showered using PYTHIA 6.4 [37].

Figure 6: (a) Contours of the $t\bar{t}(H + A)$ associated production cross-section of heavy neutral Higgs bosons at the 14 TeV LHC. (b) Contours of the $t\bar{t}(H + A)$ cross-sections at a 100 TeV $pp$-collider. (c) Contours of the $tW(H + A)$ associated production cross-section at the 14 TeV LHC. (d) Contours of the $tW(H + A)$ cross-sections at a 100 TeV $pp$-collider. The cross-sections are calculated to leading order with MadGraph using its variable factorization and renormalization scale.
with the Z2 Tune [38]. Delphes 3 [39, 40] is used to simulate the detector effects. The b-tagging efficiency from Delphes is tuned to mimic the results of the simulation by the CMS collaboration (cf. Figure 7). The mis-tagging rate of charm jets (light jets) is 20 % (1 %) [35]. We check the cut acceptances of events with same-sign top-quark pair production. The same-sign top search regions are defined as having ≥ 2 jets, $E_{T}^{miss}$ > 30 GeV and $H_{T}$ > 80 GeV. Additionally, the number of b-jets has to be either equal to one (SStop1) or greater than one (SStop2). The SStop1 (SStop2) search region acceptance (including branching fractions) is 0.43 % (0.26 %) with relative uncertainty 14 % from simulation by the CMS collaboration [35], while our result is 0.39 % (0.28 %). The results of our simulation are consistent with the results given by the CMS collaboration to within the Monte Carlo uncertainty.

Given n observed events the significance is [41]

$$Z(x|n) = \sqrt{-2 \ln \frac{L(x|n)}{L(n|n)}}$$,

(3.1)

where x is either the number of events predicted by the background only hypothesis b or by the background with signal hypothesis $b + s$ and the likelihood function is given by the Poisson probability

$$L(x|n) = \frac{x^n e^{-x}}{n!}$$.

(3.2)

For the exclusion of a model we require $Z(b + s|n) \geq 2$ and for discovery we require $Z(b|n) \geq 5$.\(^2\) For the projection to future experiments we replace the event number n with the prediction for the alternative hypothesis. Hence, we are using $Z(b + s|b) \geq 2$ and $Z(b|b + s) \geq 5$, for exclusion and discovery, respectively. Here we assume positive

\(^2\)In the case that $n < b$ we calculate the significance with the more conservative statistics also used at the Tevatron, namely $Z = \sqrt{-2 \ln \frac{L(b+s|n)}{L(b|n)}}$. This split approach corresponds to the test statistic $\tilde{q}_\mu$ in [41].
Table 1: The 2 $\sigma$ upper bounds of the number of signal events for each signal region (SR) defined in [35].

| $N_{t\text{-jets}}$ | $p_T(l)$ [GeV] | $E_{\text{miss}}$ [GeV] | $H_T$ [GeV] | $N_{\text{jets}}$ | $N_{\text{jets}}$ |
|---------------------|----------------|-------------------------|-------------|----------------|----------------|
|                     | 50–120         |                         |             | 200–400        | > 400          |
|                     | > 120          |                         |             | 200–400        | > 400          |
| $N_{\text{jets}}$  | 2–3 $\geq$ 4  | 2–3 $\geq$ 4           |             | 2–3 $\geq$ 4  | 2–3 $\geq$ 4  |
| SR01                | SR03           | SR02                    | SR04        | SR05           | SR07           |
| 0                   | > 10           | 22                      | 9.6         | 15             | 3.2            | 12             | 3.3            | 15             | 4.2            |
| > 20                | 13             | 4.0                     | 10          | 2.8            | 4.4            | 2.8            | 10             | 4.4            |
| SR11                | SR13           | SR12                    | SR14        | SR15           | SR17           |
| 1                   | > 10           | 22                      | 7.5         | 5.1            | 4.0            | 4.9            | 4.0            | 5.4            | 12             |
| > 20                | 7.5            | 4.0                     | 7.1         | 2.8            | 8.0            | 5.1            | 3.2            | 9.7            |
| SR21                | SR23           | SR22                    | SR24        | SR25           | SR27           |
| $\geq$ 2           | > 10           | 10                      | 5.4         | 3.1            | 15             | 2.7            | 2.0            | 5.0            | 4.5            |
| > 20                | 13             | 4.3                     | 3.5         | 11             | 6.5            | 2.0            | 3.7            | 4.1            |

interference between signal and background and the systematic uncertainties of the signal and the background estimation are not included in this simplified statistical procedure. Using the result in Table 7 of [35], we can give the 2 $\sigma$ upper bound of the event numbers of the new physics model for each signal region defined in [35]. The results are summarized in Table 1.

Given a number of signal events $s$ with $c_X = 1$ (where $X = H, A$) and an observed upper bound $n$ in the same signal region, the central value of the upper bound on $c_X$ is given by

$$c_X = \sqrt{\frac{n}{s}}.$$  (3.3)

The corresponding error on the bound on $c_X$ is

$$\delta c = \frac{\delta n}{2\sqrt{ns}} = \frac{c_X}{2\sqrt{n}}.$$  (3.4)

We check all of the 24 signal regions (SR01–SR08, SR11–SR18, SR21–SR28) for $H$ and $A$ with $m_{H(A)} = 400, 500, 600, 800, 1000$ GeV. The numerical simulation indicates that the strongest constraint is from the “Low-$p_T$ SR28” signal region for all of the mass points. For each mass point we consider the contributions from the $t$-channel, $s$-channel, $W$ associated production channel and 4-top channel separately and in combination. As shown in Table 2, the strongest constraint is from the 4-top channel as expected. The combined results are
Table 2: The 2σ upper bounds of the effective interaction strength $c_H$ and $c_A$ from 8TeV LHC.

| Mass [GeV] | $t$-channel | $s$-channel | $W$ associated | 4-top |
|------------|-------------|-------------|----------------|-------|
| 400        | $c_H$ 10.3 ± 2.43 91.7 ± 21.6 7.98 ± 1.87 4.47 ± 1.06 |
|            | $c_A$ 9.63 ± 2.27 123 ± 29.0 8.40 ± 1.98 4.28 ± 1.01 |
| 500        | $c_H$ 9.26 ± 2.19 130 ± 30.7 9.55 ± 2.24 5.81 ± 1.37 |
|            | $c_A$ 11.4 ± 2.69 163 ± 38.4 9.89 ± 2.33 5.37 ± 1.27 |
| 600        | $c_H$ 12.0 ± 2.83 186 ± 43.9 12.0 ± 2.82 7.55 ± 1.78 |
|            | $c_A$ 19.9 ± 4.69 228 ± 53.5 12.3 ± 2.90 6.99 ± 1.65 |
| 800        | $c_H$ 20.5 ± 4.83 531 ± 125 19.5 ± 4.56 12.7 ± 3.00 |
|            | $c_A$ 23.6 ± 5.55 441 ± 104 19.6 ± 4.62 11.9 ± 2.81 |
| 1000       | $c_H$ 36.2 ± 8.55 760 ± 179 32.1 ± 7.52 21.5 ± 5.05 |
|            | $c_A$ 40.0 ± 9.45 848 ± 200 32.1 ± 7.55 20.2 ± 4.76 |

shown in Figure 8. From this it is apparent that 8 TeV results place no meaningful limit on heavy scalar or pseudoscalar Higgses decaying to $t\bar{t}$ with $c_H, c_A \lesssim 4$.

4 Analysis strategies for future searches

We next consider the prospects for optimized searches at the 14 TeV LHC and a future 100 TeV $pp$ collider. We consider both a cut-based analysis and a BDT analysis at 14 TeV,
Table 3: Leading order cross-section times branching ratio to same-sign dileptons for the dominant backgrounds at 14TeV and 100TeV, defined such that \(ttW\pm b\) does not have an overlapping contribution with \(tt\bar{t}\). We have checked that \(ttW^-b\) is sub-dominant to \(ttW^+b\) at pp colliders and will neglect it in the further discussion.

| Background | \(14\text{TeV}\) | | | \(100\text{TeV}\) | | |
|---|---|---|---|---|---|---|
| \(tt\bar{t}\) | 0.4851 | 103 | | | 122.7 | 1.63 |
| \(tttW\pm b\) | 0.06016 | 831 | 14.86 | 6.73 |
| \(ttW^+b\) | 0.03284 | 1520 | 0.3822 | 262 |

the former providing a validation of the latter. For our 100 TeV projections we consider only a BDT analysis for simplicity, given the considerable uncertainty regarding the parameters of a 100 TeV collider. For all of these analyses we generate events in the four FS using MadGraph 2.3.3, such that the \(tW^\pm H(A)\) signal is generated with an additional soft and forward/backward \(b\)-quark. We consider only events with jets harder than 20 GeV for the LHC and 40 GeV a future collider, respectively. We have kept the spin correlation using MadSpin.

We generate the dominant irreducible backgrounds \(tt\bar{t}\) and \(tttW\pm b\), as well as the main reducible background \(ttW^+b\). Given that our main analysis strategy involves SSDL, a mass-window cut around the \(Z\) peak, at least four \(b\)-jets and a veto on the third lepton, we have verified that the background contributions from \(ttW^\pm Z\), \(ttW^\pm c\), \(tZ\), \(th\) and \(ttW^\pm\) are sub-dominant to the main backgrounds. The generated processes, their cross-sections, and the generated luminosity are summarized in Table 3.

We use Delphes 3 to simulate a detector with CMS geometry. For the 14 TeV LHC, we use a tracker coverage of \(|\eta| < 2.5\). We assume a tracker coverage of \(|\eta| < 3.5\) for detectors at future 100 TeV colliders. For all analyses we use anti-\(k_T\) jet clustering with a jet cone size of 0.5. However, in the BDT-based analysis this parameter plays a tangential role, as we additionally consider exclusively defined sub-jets as well as objects built of multiple jets.

### 4.1 Pre-selection cuts

For the analyses covering the 14 TeV LHC we apply the following pre-selection cuts: We consider only events with exactly two leptons with identical charge and transverse momenta \(p_T > 15\text{ GeV}\). The leptons must be isolated with an isolation radius of \(\Delta R > 0.3\) and a maximal transverse momentum ratio of 0.2. Where the transverse momentum ratio is defined between the lepton and other cell activity within the isolation cone. If the lepton transverse momentum is larger than 50 GeV, we do not require them to be isolated [42]. We veto on a third lepton with \(p_T > 10\text{ GeV}\). Additionally we require a minimal missing transverse energy \(E_T^{\text{miss}} > 30\text{ GeV}\) and reject events with less than four jets.

For the 100 TeV analysis we demand for the leading lepton a transverse momentum of 100 GeV. The second leading lepton must have a \(p_T > 50\text{ GeV}\) and we veto on a third lepton with \(p_T > 50\text{ GeV}\). We do not require leptons to be isolated as long as they are
harder than 100 GeV. Otherwise, we apply the same isolation cone parameter as in the case of the LHC. The missing transverse energy must be $E_T^{miss} > 60$ GeV.

4.2 Cut-based analysis for 14 TeV

For the cut based analysis we use the BoCA $b$-tag presented in Appendix A and require a minimum $b$-jet $p_T$ of 40 GeV. For this analysis we follow the ideas in [43]. We require at least four bottom jets and veto events if the invariant mass of an electron pair falls within a 20 GeV window around the $Z$-peak. We develop a cut strategy by using the rectangular cut optimization of the TMVA library [44]. The dominant cut is on the scalar sum of transverse momenta $H_T$. In order to probe a given Higgs mass $m_{H/A}$ we require $H_T > m_{H/A}$. These cuts also ensure the suppression of instrumental backgrounds, especially the misidentification of jets as well as the misidentification of lepton charges [45].

4.3 BDT analysis for 14 and 100 TeV

We focus the BDT-based search strategy on the the main features of this signal, namely

- Same sign di-lepton (SSDL)
- Heavy Higgs boson resonance
- Two additional forward/backward $b$-quarks

We apply a series of BDT-taggers designed to reconstruct the complete signal signature from its decay components following the strategy presented in [15]. Our code is based on FastJet 3.1.3 [40] and the TMVA 4.2.1 library [44] of the ROOT framework [46] and is published as
BoCA 0.2 [47]. We tag bottom-like jets, based on their displaced vertices. We exploit the fact that boosted top-like jets also show displacement but have additionally a larger jet mass. Furthermore we require or veto hard leptons inside the jet radius for hadronic and leptonic top jets, respectively. In the case of un-boosted top quarks we reconstruct the tops from their spatially separated decay products. For the reconstruction of the heavy Higgs bosons we require two tagged top-like objects. We do not reconstruct the tops of the quark pair accompanying the heavy Higgs. Instead we require two jets with large $\Delta \eta$ and high $b$-likeliness. Finally we assume that one of the tops originating from the heavy Higgs decay, decays leptonically; that another lepton is present; and that these leptons have the same charge. One example of the final BDT result at 14 TeV is presented in Figure 9.

5 Results

Here we present the results of the cut-based and BDT analyses presented in the previous section. We note that in Section 3 we presented limits individually for scalar and pseudoscalar Higgs bosons in the context of a simplified model, as 8 TeV data is insufficient to meaningfully constrain the parameter space of the MSSM. In what follows, we present limits for the sum of scalar and pseudoscalar Higgs bosons in the parameter space of $m_A$ and $\tan \beta$. We do so with an eye towards forecasting sensitivity to MSSM-like type II 2HDM in which the heavy scalar and pseudoscalar Higgs bosons are nearly degenerate.

5.1 Cut-based and BDT analyses at the 14 TeV LHC

The model-independent results for cut- and BDT-based analyses at the 14 TeV LHC are depicted separately for the three- and four-top channels in Figure 10. While the cut-based and BDT analyses have comparable sensitivity for lower masses, for larger masses the BDT-based strategy demonstrates its power as the reconstructed heavy Higgs resonance improves discrimination of signal from background. Furthermore, we would like to point out that the BDT-based analysis has an advantage in suppressing the signal over background ratio, as discussed in Appendix B. We present the combined model dependent results of the BDT analysis in Figure 12; the shaded purple regions denote the reach of the 14 TeV LHC with 300 and 3000 fb$^{-1}$. As shown in Figure 12a the top associated heavy Higgs production can exclude the lower $\tan \beta$ region up to 1 and 1.8 TeV for 300 and 3000 fb$^{-1}$, respectively. The discovery reach of the LHC presented in Figure 12b extends to 700 and 1100 GeV for the same luminosities. As already demonstrated in [15] the bottom associated heavy Higgs production covers the intermediate $\tan \beta$ region up to 1 TeV with 3000 fb$^{-1}$.

5.2 BDT analysis at a 100 TeV $pp$-Collider

The model-independent sensitivity of a 100 TeV collider is presented separately for the three- and four-top channels in Figure 11. The model-dependent combination of three- and four-top channels is depicted alongside the 14 TeV LHC reach in Figure 12. The top

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3The slight change in the shape of the limits derived from the bottom associated Higgs production with decays to a top pair compared to [15] is the result of a combination of improved background simulation and correspondingly optimized analysis.
Figure 10: (a) Model independent exclusion (orange) and discovery (green) limits at the 14 TeV LHC in the four-top channel. (b) Exclusion (orange) and discovery (green) limits in the three-top channel. The dashed limits are derived with the cut based analysis presented in Section 4.2 while the solid limits are derived with the BDT analysis presented in Section 4.3.

Figure 11: (a) Model independent limits for a future 100 TeV collider in the $t\bar{t}t\bar{t}$ channel. (b) Limits for a future 100 TeV collider in the $t\bar{t}W^\pm$ channel. Note the dominance of the three-top channel over the four-top channel especially for low masses, due to the harder lepton originating from the $W^\pm$ decay compared to the top decay (cf. Figure 2).
Figure 12: Model dependent exclusion (a) and discovery (b) limits for the 14 TeV LHC (hatched in black and purple) and a 100 TeV hadron collider (colored) derived with the BDT analysis presented in Section 4.3. The smaller bound can be reached with 0.3 and 3 ab$^{-1}$ while the large bound can be reached with 3 and 30 ab$^{-1}$ at the LHC and a future $pp$-collider, respectively. The low $\tan\beta$ region (red) is covered by the top associated heavy Higgs production with decays to top pairs. While the contribution from the $H/Abb$ vertex dominates the decays for large $\tan\beta$ we neglected its sub-leading contribution in the analysis covering small $\tan\beta$. The intermediate $\tan\beta$ region (orange) is covered by the bottom associated heavy Higgs production with decays to a top pair. The large $\tan\beta$ region (blue) is covered by the bottom associated heavy Higgs production with decays to $\tau$ lepton pairs. The latter two analyses are discussed in [15], and we revisit some aspects of the analysis in Appendix B.

-associated heavy Higgs production can exclude the lower $\tan\beta$ range up to 15 and 18 TeV for 3 and 30 ab$^{-1}$, respectively. The discovery reach extends to 10 and 15 TeV for the same luminosities. Of course, large uncertainties regarding detector properties, backgrounds, and BDT performance at 100 TeV make these limits approximate. The complementary bottom associated heavy Higgs production mode can be used to exclude the intermediate $\tan\beta$ region up to 4 and 8 GeV for 3 and 30 ab$^{-1}$, respectively. Finally the associated heavy Higgs production with two bottom quarks and decays to a $\tau$ lepton pair covers the large $\tan\beta$ range. Together, these channels cover the whole $\tan\beta$ range up to $\sim 10$ TeV.

Combining the dominance of the three-top channel over the four-top channel in Figure 11 with the larger cross-section of the three-top channel compared to the four-top channel observed in Figure 6, the $H(A)W^\pm b$ channel provides the main contribution to the limits presented in Figure 12.

6 Summary and Outlook

Heavy Higgs bosons decaying predominantly into $t\bar{t}$ final states pose an exceptional challenge to searches at hadron colliders, particularly when $bb$ associated production is negligible. This makes it difficult to probe a variety of motivated theories with heavy Higgs bosons decaying
to \( t\bar{t} \), including most notably the low \( \tan \beta \) region of the MSSM Higgs sector. In this work we have proposed probing this parameter space by searching for heavy Higgses produced in association with one and two top quarks. While these processes may be probed in a variety of final states, we have focused on searches involving same-sign dilepton pairs. We have shown that existing LHC searches at 8 TeV are sensitive to these channels, though current limits are too weak to meaningfully constrain the parameter space of heavy Higgs bosons. However, the refinement of these cut-based searches at 14 TeV will begin to meaningfully constrain the relevant parameter space. Further improvement with BDT-based analyses can potentially cover the lower part of the \( m_A-\tan \beta \) plane up to 700–1800 GeV and 10–18 TeV at the LHC and a future hadron collider, respectively. Together with the results of [14, 15] we have shown that the complete \( \tan \beta \) range can be covered with associated heavy Higgs production, while only the upper part of this range can be probed up to large masses with resonantly-produced heavy Higgs bosons. Although the sensitivity reach in this article was displayed in type II 2HDM, the proposed strategies can be used to probe the low \( \tan \beta \) region of other 2HDM as well. The sensitivity projection is straightforward.

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### A Acceptances of the BoCA SM Taggers

In order to test the BoCA SM taggers, we have generated event files containing particle pairs generated via \( t \)- and \( s \)-channel contributions. During the analysis we have required exactly one particle and one jet to fall inside the required transverse momentum window.

The BoCA bottom tagger exploits the longevity of \( B \)-mesons produced in the bottom decay and uses the radial displacement of jet tracks in order to discriminate against other jets. The track positions provided by Delphes are smeared and serve as a starting point for the calculation of displacement observables, such as the track multiplicity, average displacement of tracks and the invariant mass of the displaced tracks. We do not attempt to reconstruct secondary jet vertices. The signal and background acceptances for jets with 500 GeV < \( p_T \) < 600 GeV as well as a representation of the BDT response are presented in Figure 13. Using a BDT-cut of 0.05 leads to a \( b \)-tagging rate of 71% with a \( c \)-jet fake rate of 18%, while the misidentification rate for light quarks and gluon jets is 1.4% and 6.4%, respectively.

The BoCA tagger for hadronically decaying tops is based on the bottom tagger and a \( W \)-tagger. Additionally, it takes the kinematic variables between these two particles into account, such as the rapidity difference and the opening angle \( \Delta R \). Two representations of the top tagger BDT response are shown in Figure 14. In order to compare the performance
of the BoCA top tagger to existing top taggers, we have incorporated the \textsc{HETopTagger} \cite{48} into the BoCA code.\footnote{During finalization of this article the code for the second version of the \textsc{HETopTagger} \cite{49} has been published. We leave the comparison of the BoCA top tagger to this new version for a future publication.} While the \textsc{HETopTagger} is optimized for top (fat-)jet tagging the BoCA top-tagger also combines multiple jets in order to reconstruct less boosted top jets. For the purposes of comparison, we require exactly one top particle and one reconstructed top to have a transverse momentum between $750 \text{ GeV} < \pT < 1 \text{ TeV}$. In order to create a range of signal acceptances with the \textsc{HETopTagger} we initially do not cut on the top mass.
Figure 15: Top tagger acceptances for top jets with an transverse momentum between $750 \text{ GeV} < p_T < 1 \text{ TeV}$ at the 14 TeV LHC. (a) Signal acceptance calculated using the BoCA top tagger with Delphes jets with a jet cone size of 0.5. (b) Signal acceptance calculated using the HEPTopTagger without a prior on the top mass using optimally clustered jets with a jet cone size of 0.462.

B Comparison between cut- and BDT-based approaches in $pp \rightarrow Hbb$

In [15] we have analyzed the process $pp \rightarrow Hbb$ against the inclusive $t\bar{t}$ background. The authors of the recent publication [17] have attempted to exclude the same signal using a simple cut-based approach. Their conclusion is that the small signal over background ratio makes it impossible to exclude relevant models even when $\frac{\sigma}{\mathcal{B}}$ is appreciable. Hence we would like to explicitly demonstrate that a BDT-based approach improves the background rejection ($\frac{\sigma}{\mathcal{B}}$) to the level demanded in [17]. In order to ensure comparability we use Figure 7 of [17] as a starting point for our discussion. The cross section of the model used in [17] as well as the best exclusion limit derived in this paper are plotted as dotted lines in Figure 16. The cut-based analysis in [17] makes use of the transverse momenta of the four leading jets and the leading lepton, the scalar $H_T$, and the bottom number. We call this set of variables Var$_1$ and have applied it in both a cut- and a BDT-based analysis. Which leads to results comparable to those derived in [17]. In [15] we have reconstructed the complete event signature and used a large set of variables. This set of variables contains the BDT of all reconstructed objects, the ratios between their kinematic observables, as well as the

\footnote{The authors of [17] point out that they found a $b$-quark distribution which differs from the one presented in [15]. We have traced this difference back to deviations in the plot parameters. While we plot the $b$-quarks sorted by rapidity, the authors of [17] plot the $b$-quarks sorted by their transverse momentum. We thank the authors of [17] for clarifying their analysis.}
Figure 16: Comparison of model independent exclusion cross section requiring a significance of $Z(b + s|b) \geq 2$ (solid) and a background suppression of $\frac{s}{b} \geq 1\%$ (dashed). Applying the set of seven basic variables ($\text{Var}_1 = \{p_T(j_1), p_T(j_2), p_T(j_3), p_T(j_4), p_T(l_1), H_T, \#b\}$) used in Reference [17] (dotted green) leads in our analysis to comparable results with both cut- and BDT based approaches (dashed blue). If we reconstruct the heavy Higgs boson and apply $\text{Var}_1$ (brown) we are able to significantly increase the background suppression. Using the technique described in [15] with the lepton isolation used in this publication (orange) leads once more to a notable improvement. In [15] we have only considered hard leptons, in this analysis we use hard leptons as well as isolated soft leptons. In the legend we use "*" to denote this difference.

References

[1] ATLAS Collaboration, G. Aad et al., Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, JHEP 02 (2013) 095, [arXiv:1211.6956].

[2] ATLAS Collaboration, G. Aad et al., Search for neutral Higgs bosons of the minimal supersymmetric standard model in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, JHEP 11 (2014) 056, [arXiv:1409.6064].

[3] ATLAS Collaboration, G. Aad et al., Search for a CP-odd Higgs boson decaying to $Z\ell$ in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B744 (2015) 163–183, [arXiv:1502.04478].

[4] ATLAS Collaboration, G. Aad et al., Search for an additional, heavy Higgs boson in the $H \rightarrow ZZ$ decay channel at $\sqrt{s} = 8$ TeV in $pp$ collision data with the ATLAS detector, arXiv:1507.05930.
ATLAS Collaboration, G. Aad et al., Constraints on non-Standard Model Higgs boson interactions in an effective Lagrangian using differential cross sections measured in the $H \rightarrow \gamma\gamma$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector, arXiv:1508.02507.

ATLAS Collaboration, G. Aad et al., Search for a high-mass Higgs boson decaying to a $W$ boson pair in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, arXiv:1509.00389.

CMS Collaboration, V. Khachatryan et al., Searches for heavy Higgs bosons in two-Higgs-doublet models and for $t\bar{t}h$ decay using multilepton and diphoton final states in $pp$ collisions at 8 TeV, Phys. Rev. D90 (2014) 112013, [arXiv:1410.2751].

CMS Collaboration, V. Khachatryan et al., Search for Neutral MSSM Higgs Bosons Decaying into A Pair of Bottom Quarks, JHEP 11 (2015) 071, [arXiv:1506.08329].

CMS Collaboration, V. Khachatryan et al., Search for Neutral MSSM Higgs Bosons Decaying to $\mu^+\mu^-$ in $pp$ Collisions at $\sqrt{s}=7$ and 8 TeV, arXiv:1508.01437.

ATLAS Collaboration, G. Aad et al., Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu$ in fully hadronic final states using $pp$ collision data at $\sqrt{s}=8$ TeV with the ATLAS detector, JHEP 03 (2015) 088, [arXiv:1412.6663].

ATLAS Collaboration, G. Aad et al., Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay $H^\pm \rightarrow W^\pm Z$ using $pp$ Collisions at $\sqrt{s}=8$ TeV with the ATLAS Experiment, Phys. Rev. Lett. 114 (2015), no. 23 231801, [arXiv:1503.04233].

CMS Collaboration, V. Khachatryan et al., Search for a charged Higgs boson in $pp$ collisions at $\sqrt{s}=8$ TeV, JHEP 11 (2015) 018, [arXiv:1508.07774].

P. S. Bhupal Dev and A. Pilaftsis, Maximally Symmetric Two Higgs Doublet Model with Natural Standard Model Alignment, JHEP 12 (2014) 024, [arXiv:1408.3405]. [Erratum: JHEP 11,147(2015)].

N. Craig, F. D’Eramo, P. Draper, S. Thomas, and H. Zhang, The Hunt for the Rest of the Higgs Bosons, arXiv:1504.04630.

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, Heavy Higgs Bosons at 14 TeV and 100 TeV, JHEP 11 (11, 2015) 124, [arXiv:1504.07617].

B. Bhattacherjee, A. Chakraborty, and A. Choudhury, Status of the MSSM Higgs sector using global analysis and direct search bounds, and future prospects at the High Luminosity LHC, Phys. Rev. D92 (2015), no. 9 093007, [arXiv:1504.04308].

S. Gori, I.-W. Kim, N. R. Shah, and K. M. Zurek, Closing the Wedge: Search Strategies for Extended Higgs Sectors with Heavy Flavor Final States, arXiv:1602.02782.

K. J. F. Gaemers and F. Hoogeveen, Higgs Production and Decay Into Heavy Flavors With The Gluon Fusion Mechanism, Phys. Lett. B146 (1984) 347.

D. Dicus, A. Stange, and S. Willenbrock, Higgs decay to top quarks at hadron colliders, Phys.Lett. B333 (1994) 126–131, [hep-ph/9404359].

R. Frederix and F. Maltoni, Top pair invariant mass distribution: A Window on new physics, JHEP 0901 (2009) 047, [arXiv:0712.2355].

S. Jung, J. Song, and Y. W. Yoon, Dip or nothingness of a Higgs resonance from the interference with a complex phase, Phys. Rev. D92 (2015), no. 5 055009, [arXiv:1505.00291].

T. Han, G. Valencia, and Y. Wang, Hadron collider signatures for new interactions of top and bottom quarks, Phys. Rev. D70 (2004) 034002, [hep-ph/0405055].
[23] B. Lillie, J. Shu, and T. M. P. Tait, *Top Compositeness at the Tevatron and LHC*, JHEP 04 (2008) 087, [arXiv:0712.3057].

[24] B. S. Acharya, P. Grajek, G. L. Kane, E. Kuflik, K. Suruliz, and L.-T. Wang, *Identifying Multi-Top Events from Gluino Decay at the LHC*, arXiv:0901.3367.

[25] N. Chen, J. Li, and Y. Liu, *LHC searches for heavy neutral Higgs bosons with a top jet substructure analysis*, arXiv:1509.03848.

[26] J. F. Gunion and H. E. Haber, *The CP conserving two Higgs doublet model: The Approach to the decoupling limit*, Phys. Rev. D67 (2003) 075019, [hep-ph/0207010].

[27] N. Craig and S. Thomas, *Exclusive Signals of an Extended Higgs Sector*, JHEP 11 (2012) 083, [arXiv:1207.4835].

[28] N. Craig, J. Galloway, and S. Thomas, *Searching for Signs of the Second Higgs Doublet*, arXiv:1305.2424.

[29] M. Carena, I. Low, N. R. Shah, and C. E. M. Wagner, *Impersonating the Standard Model Higgs Boson: Alignment without Decoupling*, JHEP 04 (2014) 015, [arXiv:1310.2248].

[30] H. E. Haber, *The Higgs data and the Decoupling Limit*, in 1st Toyama International Workshop on Higgs as a Probe of New Physics 2013 (HPNP2013) Toyama, Japan, February 13-16, 2013, arXiv:1401.0152.

[31] F. Maltoni, K. Paul, T. Stelzer, and S. Willenbrock, *Associated production of Higgs and single top at hadron colliders*, Phys. Rev. D64 (2001) 094023, [hep-ph/0106293].

[32] F. Demartin, F. Maltoni, K. Mawatari, and M. Zaro, *Higgs production in association with a single top quark at the LHC*, Eur. Phys. J. C75 (2015), no. 6 267, [arXiv:1504.00611].

[33] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP 1407 (2014) 079, [1405.0301].

[34] S. Dulat, T. J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *The CT14 Global Analysis of Quantum Chromodynamics*, arXiv:1506.07443.

[35] CMS Collaboration, S. Chatrchyan et al., *Search for new physics in events with same-sign dileptons and jets in pp collisions at \(\sqrt{s} = 8\) TeV*, JHEP 1401 (2014) 163, [1311.6736].

[36] J. Pumplin, D. Stump, J. Huston, H. Lai, P. M. Nadolsky, et al., *New generation of parton distributions with uncertainties from global QCD analysis*, JHEP 0207 (2002) 012, [hep-ph/0201195].

[37] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP 0605 (2006) 026, [hep-ph/0603175].

[38] R. Field, *Min-Bias and the Underlying Event at the LHC*, Acta Phys.Polon. B42 (2011) 2631–2656, [1110.5530].

[39] DELPHES 3 Collaboration, J. de Favereau et al., *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, JHEP 1402 (2014) 057, [1307.6346].

[40] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet User Manual*, Eur.Phys.J. C72 (2012) 1896, [1111.6097].
[41] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C71 (2011) 1554, [arXiv:1007.1727]. [Erratum: Eur. Phys. J.C73,2501(2013)].

[42] C. Brust, P. Maksimovic, A. Sady, P. Saraswat, M. T. Walters, and Y. Xin, *Identifying boosted new physics with non-isolated leptons*, JHEP 04 (2015) 079, [arXiv:1410.0362].

[43] ATLAS Collaboration, G. Aad et al., *Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP 10 (2015) 150, [arXiv:1504.04605].

[44] A. Hocker, J. Stelzer, F. Tegenfeldt, H. Voss, K. Voss, et al., *TMVA - Toolkit for Multivariate Data Analysis*, PoS ACAT (2007) 040, [physics/0703039].

[45] ATLAS Collaboration, T. A. collaboration, *Search for new physics using events with b-jets and a pair of same charge leptons in 3.2 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, .

[46] R. Brun and F. Rademakers, *ROOT: An object oriented data analysis framework*, Nucl.Instrum.Meth. A389 (1997) 81–86.

[47] “BoCA: Boosted Collider Analysis.” [https://github.com/BoostedColliderAnalysis/BoCA](https://github.com/BoostedColliderAnalysis/BoCA), 2015. doi: 10.5281/zenodo.34201.

[48] T. Plehn, M. Spannowsky, M. Takeuchi, and D. Zerwas, *Stop Reconstruction with Tagged Tops*, JHEP 10 (2010) 078, [arXiv:1006.2833].

[49] G. Kasieczka, T. Plehn, T. Schell, T. Strebler, and G. P. Salam, *Resonance Searches with an Updated Top Tagger*, JHEP 06 (2015) 203, [arXiv:1503.05921].

[50] J. Gallicchio and M. D. Schwartz, *Seeing in Color: Jet Superstructure*, Phys. Rev. Lett. 105 (2010) 022001, [arXiv:1001.5027].