Investigation of Charged Higgs Boson in the Bottom and Top Quark Decay Channel at the FCC-hh

I. Turk Cakir
Department of Energy Systems Engineering, Giresun University, 28200 Giresun, Turkey

O. Cakir†
Department of Physics, Ankara University, 06100 Ankara, Turkey

H. Denizli‡ and A. Senol§
Department of Physics, Bolu Abant Izzet Baysal University, 14280, Bolu, Turkey

A. Yilmaz¶
Department of Electrical and Electronics Engineering, Giresun University, 28200 Giresun, Turkey

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After the recent discovery of a neutral Higgs boson with a mass about $125$ GeV, we assess the extend of discovery potential of future circular hadron collider (FCC-hh) for a charged Higgs boson in the bottom and top quark decay channel. The charged Higgs boson can be produced through the $pp \rightarrow h^- t + X$ process with a subsequent decay $h^- \rightarrow b \bar{t}$ channel. This decay channel is particularly important for studying the charged Higgs boson heavier than the top quark. We consider an extension of the standard model Higgs sector, namely two Higgs doublet model (2HDM), and perform a dedicated signal significance analysis to test this channel for the FCC-hh running at the center of mass energy of $100$ TeV and the integrated luminosity of $1 \text{ab}^{-1}$ (initial) and $30 \text{ab}^{-1}$ (ultimate). We find that an important part of the parameter spaces of two Higgs doublet model are examinable at the FCC-hh.

I. INTRODUCTION

The Higgs boson have been discovered by the ATLAS [1] and CMS [2] experiments at the CERN LHC in 2012. This discovery has motivated a lot of measurements to identify the nature of the discovered particle. We have elementary fermions (quarks and leptons) and bosons (vectors and scalar) within the standard model (SM) of particle physics. However, multiple scalars are predicted by some extensions of the standard model, such as two Higgs doublet model (2HDM) [3, 4], and supersymmetry (SUSY) [5] (and references therein), to deal with some issues such as dark matter, hierarchy, etc. In addition to neutral scalars, one can expect singly or doubly charged Higgs bosons in such models. Recently, charged Higgs boson discovery prospects have been studied in Ref. [6], which classify models into categories of different coupling properties.

At a center of mass energy of $13$ TeV in proton proton collisions, the ATLAS and CMS Collaborations have performed several searches for charged Higgs bosons [7, 8], where low values of $\tan \beta < 1$ are excluded for a charged Higgs boson mass up to $160$ GeV. The most stringent upper limit from ATLAS on $\sigma(pp \rightarrow h^+ t + X) \times B(h^+ \rightarrow \tau^+ \nu)$ and $\sigma(pp \rightarrow h^+ t + X) \times B(h^+ \rightarrow t \bar{b})$ at $95\%$ CL is in the range $4.2 - 0.0025$ pb and $9.6 - 0.01$ pb for a charged Higgs boson mass in the range $90 - 2000$ GeV [7] and $200 - 3000$ GeV [9], respectively.

We study charged Higgs boson at the future circular hadron collider (FCC-hh) with center of mass energy of $100$ TeV [10]. We concentrate on the 2HDM model type-II scenario or MSSM scenario. In the second section we mention about signal process as well as corresponding SM backgrounds. Event selection via objects in the final state have been performed over the signal and background samples within the FCC software (FCCSW) [11]. The cross sections for the process $pp \rightarrow h^- t + X$ have been calculated for different model parameters. Kinematic distributions of final state objects and cut flows presented in the next section. Reconstruction of charged Higgs boson and its invariant mass distribution is given in the third section. Finally, statistical significance of the signal have been calculated depending on the parameter space (mass and couplings) of the model framework. Finally, we draw a conclusion on the search for charged Higgs boson at the FCC-hh.

II. SIGNAL AND BACKGROUND

For the signal, we use the scalar potential and the Yukawa sector of the general 2HDM [3], in which the complex (pseudo) scalar doublets $\Phi_j (j = 1, 2)$ can be parametrized as
where $v_{1,2}$ are vacuum expectation values of two Higgs doublets satisfying $v = \sqrt{v_1^2 + v_2^2}$ with $v \simeq 246$ GeV. The ratio of the vacuum expectation values is defined $v_1/v_2 = \tan \beta$ as a free parameter. Two CP-even physical field can be written in terms of two neutral scalar fields

$$\Phi_j(x) = \left( \begin{array}{c} \phi_j^+(x) \\ \sqrt{2} [v_j + \phi_j^0(x) + i G_j(x)] \end{array} \right) \quad (1)$$

where $H^0$ and $h^0$ are the CP-even neutral field $A^0 = -G_1 \sin \beta + G_2 \cos \beta$ and charged field $h^{\pm} = -\phi_1^\pm \sin \beta + \phi_2^\pm \cos \beta$.

After electroweak symmetry breaking, five degrees of freedom become physical Higgs bosons (three neutral $h^0, H^0, A^0$ and two charged $h^+, h^-$), while three degrees of freedom kept by Goldstone bosons (neutral $G^0$ and charged $G^+, G^-$) to attribute massive longitudinal component of gauge fields (corresponding to neutral $Z^0$ and charged $W^+, W^-$. bosons). The other independent parameters are the masses ($m_{h^0}, m_{H^0}, m_A, m_{h^\pm}$) of the physical Higgs bosons in the alignment limit.

The cross section for signal process $pp \to h^-t + X$ can be calculated at leading order integrating over parton distribution functions through the subprocess $gb \to h^-t$ partonic cross section.

$$\sigma(pp \to h^-t + X) = \int x_1 \int x_2 \sigma(gb \to h^-t) \times dx_1 dx_2 f_1(x_1, \mu_F) f_2(x_2, \mu_F) \quad (3)$$

where $f_i(x_i, \mu_F)$ are parton distribution functions inside each proton (hadron momentum $h_i$) with the parton momentum ($p_i$) fractions $x_i = p_i/h_i$. The limits of the integrals are defined as $x_{1\max} = 1$ and $(x_1 x_2)_{\min} = \tau_{\min} = \delta_{\min}/s$ (where $\sqrt{s}$ is the process center of mass energy of FCC-hh taken as 100 TeV). The partonic cross section for the subprocess $\sigma(gb \to h^-t)$ can be calculated from the process kinematics and the matrix elements. The matrix element squared expressions ($M_{2 \to 2}$) averaged over initial state (spins, colors) and summed over final state (spins, colors) for subprocess $gb \to h^-t$ is given by

$$\langle |M_{2 \to 2}|^2 \rangle = \frac{1}{24 s_W^2 \tan^2 \beta m_W^2} \times \left\{ A_1(\hat{s}, \hat{t}, m_{h^-}) + A_2(\hat{s}) \tan^2 \beta \right\}$$

where the Mandelstam variables $\hat{s} = (p_1 + p_2)^2$, $\hat{t} = (p_1 - p_2)^2$ and $\hat{u} = (p_1 - p_4)^2 = -\hat{s} + m_b^2 + m_t^2 + m_{h^-}^2$ are used to shorten the amplitude of the signal subprocess in Lorentz invariant form. The coefficients $A_1(\hat{s}, \hat{t}, m_{h^-})$ are written in terms of the variables and they are given in detail in the Appendix. In Eq. 4 the terms with coefficients $A_2(\hat{s}, A_5(\hat{t}, m_{h^-})$, $A_6(\hat{s}, \hat{t}, m_{h^-})$ are independent of $\tan \beta$, while the others can be written in terms of a function depending on $\tan \beta$. When the mass of b-quark is neglected the matrix element squared expression will depend on $1/\tan^2 \beta$ as explained in the Appendix.

The matrix element squared expression ($M_{1 \to 2}$) of decay process ($h^- \to bl$) is given by

$$\langle |M_{1 \to 2}|^2 \rangle = \frac{3}{2} \frac{g_b^2 |V_{ub}|^2}{s_W^2 m_W^2 \tan^2 \beta} \times \left[ m_t^2 m_{h^-}^2 - m_b^2 \tan^2 \beta - m_b^2 + m_b^2 (1 + 4 \tan^2 \beta + \tan^4 \beta) \right]$$

where the signal samples of the process $pp \to h^-t$ are followed by the decay mode $h^- \to bl$ leading to an intermediate state of a pair of top quarks and a b-quark. We use Pythia 8 package [12] for the signal event generation, where the subprocess $gb \to h^-t$ already exists in the publicly available software. The respective Feynman diagrams for the signal process are presented in Fig. 1.
The decay chain, in general, ends with three possible channels depending on the decay channels of a pair of $W$ bosons: (i) all hadronic mode (7 jets: 4 light jets and 3 $b$-jets), (ii) single lepton mode (1 charged lepton and missing transverse energy, 2 light jets and 3 $b$-jets), (iii) dilepton mode (2 oppositely charged leptons and missing transverse energy, 3 $b$-jets). We may generalize the final state by including different types of fermion particles ($f_i$) and $b$-jets ($b_j$) such as $f_1 f_2 f_3 f_4 b_1 b_2 b_3$. Here, we focus on the final state including single lepton mode of the signal: 1 lepton + MET + 3 $b$-jet $+ 2$ jets.

Signal events are generated with Pythia 8 within the FCC software (FCCSW) \[11\] for different model parameters: mass ($m_{h^-} = m_{H^0}$) in the range of (500 - 2000) GeV, ratio of the vacuum expectation values (tan $\beta$) in the range of (1 - 30), and a parameter $\cos(\beta - \alpha) = 0$ (alignment limit) which is relevant for $H^{0}V^{0}$, $h^0AZ$ and $h^0h^{\pm}W^{\pm}$ couplings. However, the background Les Houches events (LHE) are generated with MadGraph 5 \[13\]. For further hadronization and showering for signal and background events are performed through Pythia 8 within this software. A fast detector simulation is performed with Delphes 3 \[13\] for parametric card (FCChh.tcl) of an FCC-hh detector. Event selection is applied on those samples with Heppy \[15\]. Flat ntuples are produced with observables of interest and analyzed with Heppy. It reads events in FCC EDM format, and creates lists of objects adapted to an analysis in python. The gen-level and reco-level plots are produced with python scripts where Heppy writes a Root program \[15\] tree.

Background samples for the processes $pp \to t\bar{t}$, $pp \to t\bar{t}bj$ and $pp \to tjbj$ are simulated using Delphes 3 with FCC-hh detector card. The main background is $t\bar{t}+jets$, in particular $t\bar{t}+bj$ in the most signal-sensitive regions.

### Table I. Decay width for process $h^- \to b\bar{t}$ depending on parameter $\tan \beta$ values and different mass values.

| $m_{h^-}$ (GeV) | $\tan \beta = 1$ | $\tan \beta = 7$ | $\tan \beta = 10$ | $\tan \beta = 30$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 500 GeV         | 23.46           | 0.8697          | 1.037           | 7.281           |
| 1000 GeV        | 56.93           | 2.118           | 2.524           | 17.64           |
| 2000 GeV        | 119.20          | 4.437           | 5.286           | 36.99           |

Figure 1. Feynman diagrams for subprocess $gb \to h^- t \to b\bar{t}t$.

### III. ANALYSIS AND RESULTS

For the signal cross section calculation we have performed benchmarking of the parameter space of the model considered here, requiring the mass $m_{h^-}$ to lie in the 500 GeV–2000 GeV range. We find signal cross sections (from Pythia 8 with generator level defaults) as shown in Table II by taking tan $\beta$ variable and setting $\cos(\beta - \alpha) = 0$. The bottom rows of Table II show the cross sections for relevant SM backgrounds obtained using MadGraph 5.

Both the signal and background samples are analysed with python scripts by reading Root trees. Events are selected as the presence of required number of objects in the final state. We deal with events including at least 5 jets ($n_{jet} \geq 5$) where there is at least two $b$-jets. In addition, we require one lepton (electron or muon) and a significant MET (focusing on $1l + MET + 5jets$). At the end of the analysis histograms are printed as figure files. The distributions of kinematical variables ($p_T$ of jets and leptons, $\eta$ of jets and leptons) for the final state objects are presented in Fig. 2 and 3 for the signal events with mass $m_{h^-} = 1000$ GeV and $m_{h^-} = 2000$ GeV, respectively. In Fig. 4 and 5, the hadronic transverse energy ($H_T$) for jets, missing transverse energy (MET) and lepton (both electron ($e$) and electron+muon ($e+\mu$)) kinematical distributions ($p_T$ and $\eta$) for signal with mass $m_{h^-} = 1000$ GeV and $m_{h^-} = 2000$ GeV, respectively.

The charged Higgs boson mass is reconstructed from one top (reconstructed from the hadronically decaying W boson and subleading $b$-jet) and the leading $b$-jet candidate. Further steps are followed as the isolation criteria for one electron or muon (initiated from the leptonically decaying W boson), rejection of events with additional muon or electron candidates, removal of electrons or muons if the are separated from the nearest jet by $\Delta R < 0.4$. The cut flow for the analysis is shown in Table III.

Invariant mass distribution of four jets initiated from bottom (leading $b$-jet) and top quark are presented in Fig. 6 for charged Higgs boson signal with masses $m_{h^-} = 500$ GeV, $m_{h^-} = 1000$ GeV and $m_{h^-} = 2000$ GeV.

We calculate statistical significance (SS) from signal ($N_S$) and background ($N_B$) events within the interval $|m_{tb} - m_{h^-}| < 0.4m_{h^-}$, where significance is defined as
Figure 2. Transverse momentum and rapidity distributions of final state detectable objects (jets, electron or muon) for signal (mass $m_{h^-} = 1000$ GeV).

Figure 3. The same as Fig. 2 but for the charged Higgs boson mass $m_{h^-} = 2000$ GeV.

Table III. The cut flow for the analysis of single lepton and MET, and at least five jets channel from charged Higgs boson associated with top quark.

| Object                          | Requirement                      |
|--------------------------------|----------------------------------|
| Single electron or muon        | $p_T > 30$ GeV, $|\eta| < 3.0$ |
| At least five jets ($n_{jet} \geq 5$) | $p_T > 30$ GeV, $|\eta| < 3.0$ |
| At least two $b$-jet ($n_b \geq 2$) | $p_T > 30$ GeV, $|\eta| < 3.0$ |
| Missing $p_T$                  | $p_T > 30$ GeV                   |
| $(l, j)$ and $(j, j)$ separation | $\Delta R(l, j) > 0.4; \Delta R(j, j) > 0.4$ |
| Hadronic transverse energy     | $H_T > 350$ GeV                  |
| Reco top mass range            | $130 < m_{Wb} < 200$ GeV         |
| Reco $h^-$ mass range          | $|m_{tb} - m_{h^-}| < 0.4m_{h^-}$ |

$SS = \sqrt{2 \left[ (N_S + N_B) \ln(1 + \frac{N_S}{N_B}) - N_S \right]}$

Number of signal and background events and statistical significance for the integrated luminosity of $L = 1$ ab$^{-1}$ (initial) and $L = 30$ ab$^{-1}$ (ultimate) at FCC-hh are given in Table IV.

IV. CONCLUSION

We have studied the charged Higgs boson (predicted by the 2HDM type-II or MSSM) and top quark associated production in proton-proton collisions at the FCC-
Figure 6. Invariant mass distribution of four jets initiated from bottom and top quark decays for signal with masses $m_{h^-} = 500$ GeV, $m_{h^-} = 1000$ GeV (upper pad) and $m_{h^-} = 2000$ GeV (lower pad).

Table IV. Number of signal ($N_S$) and background ($N_B$) events within the $\Delta m = \pm 0.4 m_{h^-}$ interval and statistical significance (SS) for the integrated luminosity of $L = 1$ ab$^{-1}$ and $L = 30$ ab$^{-1}$ at FCC-hh.

| Mass (GeV) | $N_B(\Delta m)$ | $N_S(\Delta m)$ | SS(1) | SS(30) |
|------------|------------------|------------------|--------|--------|
| 500        | 368662140        | 1                | 148.34 | 812.49 |
| 1000       | 234516253        | 7                | 95340  | 29.17  |
| 2000       | 61585260         | 10               | 105201 | 5.47   |
|            |                  | 30               | 697536 | 36.32  |
|            |                  | 1                | 327598 | 21.38  |
|            |                  | 7                | 10993  | 0.720  |
|            |                  | 12               | 12013  | 0.780  |
|            |                  | 30               | 77940  | 5.08   |
|            |                  | 1                | 22825  | 2.91   |
|            |                  | 7                | 764    | 0.097  |
|            |                  | 10               | 835    | 0.106  |
|            |                  | 30               | 5316   | 0.671  |

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APPENDIX

The coefficients of the terms in the matrix element squared (Eq. (4)) are given:

$$A_1(\hat{s}, \hat{t}, m_{h^-}) = m_t^2 \left[ m_b^2 + m_t^2 (3m_{h^-}^2 - 2m_t^2 - 4\hat{s} - \hat{t}) + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2) \right]$$

$$A_2(\hat{s}) = -4m_{h^-}^2 t_m^2 \left( m_b^2 + \hat{s} \right)$$

$$A_3(\hat{s}, \hat{t}, m_{h^-}) = m_b^2 \left[ m_b^2 + m_{h^-}^2 (3m_{h^-}^2 - 2m_t^2 - 4\hat{s} - \hat{t}) + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2) \right]$$

When the mass of $b$-quark ($m_b$) is neglected, these terms reduces to a simplified form of coefficients:

$$A_4(\hat{s}, \hat{t}, m_{h^-}) = 2m_t^2 \left[ m_b^2 - m_t^4 + m_t^2 \hat{s} + \hat{s}^2 \right]$$

$$A_5(t, m_{h^-}) = 4m_t^2 t_m^2 \left[ -2m_b^2 + m_{h^-}^2 - 2m_t^2 + \hat{t} \right]$$

$$A_6(\hat{t}, \hat{s}, m_{h^-}) = 2m_b^2 \left[ m_b^2 + m_t^2 \hat{s} + \hat{s}^2 \right]$$

$$A_7(\hat{s}, \hat{t}, m_{h^-}) = m_t^2 \left[ m_b^2 - 2m_t^4 \hat{s} + \hat{s}^2 \right]$$

$$A_8(\hat{s}, \hat{t}, m_{h^-}) = -4m_t^2 t_m^2 \left( m_b^2 + m_{h^-}^2 + 2m_t^2 - \hat{s} - \hat{t} \right)$$

$$A_9(\hat{s}, \hat{t}, m_{h^-}) = m_b^2 \left[ m_b^2 - 2m_t^4 \hat{s} + \hat{s}^2 \right]$$

and all other coefficients vanish. In this case hadronic cross section $\sigma(\hat{s}, m_{h^-})$ will be proportional to $1/\tan^2 \beta$ as mentioned in the text.
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