



# Investigation of charged Higgs boson in the bottom and top quark decay channel at the FCC-hh

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## ABSTRACT

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),  $3 \text{ ab}^{-1}$  (comparison with HL-LHC) and  $30 \text{ ab}^{-1}$  (ultimate). We find that an important part of the parameter spaces of two Higgs doublet model is examinable at the FCC-hh.

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## 1. Introduction

The Higgs boson has 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  $\sigma(pp \rightarrow h^+ t + X) \times \mathcal{B}(h^+ \rightarrow \tau^+ \nu)$  and  $\sigma(pp \rightarrow h^+ t + X) \times \mathcal{B}(h^+ \rightarrow t\bar{b})$  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. However, some parts of parameter space for charged Higgs bosons are still relevant in light of the LHC results.

The discovery potential ( $5\sigma$ ) of the high luminosity LHC (HL-LHC with  $\sqrt{s} = 14 \text{ TeV}$  and  $L_{int} = 3 \text{ ab}^{-1}$ ) for charged Higgs boson production (in association with top quark) and decay channel  $h^\pm \rightarrow \tau^\pm \nu_\tau$  has been presented for a mass range of  $m_{h^\pm} = 370\text{--}800 \text{ GeV}$  at the moderate values of  $\tan\beta$  by Ref. [10].

The physics opportunities for the study of the SM and non-SM Higgses at the future 100 TeV  $pp$  collider have been summarized within the report [11]. The exotic decay modes of non-SM Higgses in models with extended Higgs sectors have been studied in [12], which can probe most of the region of the Type-II 2HDM parameter space. These modes with sizable exotic decay branching fractions, make them complementary to the conventional decay channels for non-SM Higgses.

We study charged Higgs boson at the FCC-hh with center of mass energy of 100 TeV [13]. We concentrate on the 2HDM model type-II scenario or MSSM scenario. For the charged Higgs bosons  $h^\pm$  masses well above the top quark mass ( $m_{h^\pm} > m_t + m_b$ ), the leading decay mode is  $h^- \rightarrow b\bar{t}$  in a broad range of models [14]. In

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particular, this is the preferred decay mode in both the decoupling limit scenario and the alignment limit  $\cos(\beta - \alpha) \simeq 0$ , where the lightest CP-even neutral Higgs boson of the extended Higgs sector has properties similar to those of the SM Higgs boson. However, the branching fraction of  $h^\pm \rightarrow \tau^\pm \nu$  mode can reach 10–15% at large values of  $\tan\beta$  in a type-II 2HDM. Therefore, the  $h^- \rightarrow b\bar{t}$  and  $h^- \rightarrow \tau^- \bar{\nu}$  decays naturally complement each other in searches for charged Higgs bosons at future hadron colliders [15]. In the second section we mention about signal process as well as corresponding SM backgrounds. Event selection via objects in the final state has been performed over the signal and background samples within the FCC software (FCCSW) [16]. 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 has 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.

## 2. 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

$$\Phi_j(x) = \begin{pmatrix} \phi_j^+(x) \\ \frac{1}{\sqrt{2}}[v_j + \phi_j^0(x) + iG_j(x)] \end{pmatrix} \quad (1)$$

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

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \quad (2)$$

and the CP-odd 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  $h^\pm, h^\pm$ ), while three degrees of freedom kept by Goldstone bosons (neutral  $G^0$  and charged  $G^\pm$ ) to attribute massive longitudinal component of gauge fields (corresponding to neutral  $Z^0$  and charged  $W^\pm$  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  $pp \rightarrow h^- t + X$  can be calculated at leading order integrating over parton distribution functions through the subprocess  $gb \rightarrow h^- t$  partonic cross section.

$$\sigma(pp \rightarrow h^- t + X) = \int_{x_{1min}}^{x_{1max}} \int_{x_{2min}}^{x_{2max}} \hat{\sigma}(gb \rightarrow h^- t) \times dx_1 dx_2 f_1(x_1, \mu_F) f_2(x_2, \mu_F) \quad (3)$$

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  $x_{imax} = 1$  and  $(x_1 x_2)_{min} = \tau_{min} = \hat{s}_{min}/s$  (where  $\sqrt{s}$  is the process center of mass energy of FCC-hh taken as 100 TeV). The partonic cross section  $\hat{\sigma}(gb \rightarrow h^- t)$  for the subprocess can be calculated from the process kinematics and the matrix elements. The matrix element

**Table 1**

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

$\Gamma$ (GeV)	$\tan\beta = 1$	$\tan\beta = 7$	$\tan\beta = 10$	$\tan\beta = 30$
$m_{h^-} = 500$ GeV	23.46	0.8697	1.037	7.281
$m_{h^-} = 1000$ GeV	56.93	2.118	2.524	17.67
$m_{h^-} = 2000$ GeV	119.20	4.437	5.286	36.99

( $M_{2 \rightarrow 2}$ ) squared expressions averaged over initial state (spins, colors) and summed over final state (spins, colors) for ( $2 \rightarrow 2$ ) subprocess  $g(p_1)b(p_2) \rightarrow h^-(p_3)t(p_4)$  is given by

$$\begin{aligned} \langle |M_{2 \rightarrow 2}|^2 \rangle &= \frac{1}{24} \frac{g_e^2 g_s^2 |V_{tb}|^2}{s_W^2 \tan^2 \beta m_W^2} \\ &\times \left\{ \frac{A_1(\hat{s}, \hat{t}, m_{h^-}) + A_2(\hat{s}) \tan^2 \beta}{(\hat{s} - m_b^2)^2} \right. \\ &+ \frac{A_3(\hat{s}, \hat{t}, m_{h^-}) \tan^4 \beta}{(\hat{s} - m_b^2)^2} \\ &+ \frac{A_4(\hat{s}, \hat{t}, m_{h^-}) + A_5(\hat{t}, m_{h^-}) \tan^2 \beta}{(\hat{s} - m_b^2)(\hat{u} - m_t^2)} \\ &+ \frac{A_6(\hat{s}, \hat{t}, m_{h^-}) \tan^4 \beta}{(\hat{s} - m_b^2)(\hat{u} - m_t^2)} \\ &+ \frac{A_7(\hat{s}, \hat{t}, m_{h^-}) + A_8(\hat{s}, \hat{t}, m_{h^-}) \tan^2 \beta}{(\hat{u} - m_t^2)^2} \\ &\left. + \frac{A_9(\hat{s}, \hat{t}, m_{h^-}) \tan^4 \beta}{(\hat{u} - m_t^2)^2} \right\} \quad (4) \end{aligned}$$

where the Mandelstam variables  $\hat{s} = (p_1 + p_2)^2$ ,  $\hat{t} = (p_1 - p_3)^2$  and  $\hat{u} = (p_1 - p_4)^2 = -\hat{s} - \hat{t} + m_b^2 + m_t^2 + m_{h^-}^2$  are used to shorten the amplitude of the signal subprocess in Lorentz invariant form. The coefficients  $A_i(\hat{s}, \hat{t}, m_{h^-})$  are written in terms of the variables and they are given in detail in the Appendix. In Eq. (4), the terms with coefficients  $A_2(\hat{s})$ ,  $A_5(\hat{t}, m_{h^-})$ ,  $A_8(\hat{s}, \hat{t}, m_{h^-})$  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 ( $M_{1 \rightarrow 2}$ ) squared expression for decay process ( $h^- \rightarrow b\bar{t}$ ) is given by

$$\begin{aligned} \langle |M_{1 \rightarrow 2}|^2 \rangle &= \frac{3}{2} \frac{g_e^2 |V_{tb}|^2}{s_W^2 m_W^2 \tan^2 \beta} \\ &\times \left[ m_t^2 m_{h^-}^2 - m_b^4 \tan^4 \beta - m_t^4 \right. \\ &\left. + m_b^2 (m_{h^-}^2 \tan^4 \beta - m_t^2 (1 + 4 \tan^2 \beta + \tan^4 \beta)) \right] \quad (5) \end{aligned}$$

where  $g_e$  and  $g_s$  are the electromagnetic coupling and strong coupling corresponding to  $U(1)_Q$  and  $SU(3)_C$  gauge groups, the  $s_W$  is the sinus of Weinberg weak mixing angle  $\theta_W$ , and  $V_{tb}$  is the relevant CKM matrix element. From the expressions Eq. (4) and (5), we obtain the  $\tan\beta$  dependence of the cross section and decay width calculations. We present decay width  $\Gamma(h^- \rightarrow b\bar{t})$  values in Table 1, depending on the parameter  $\tan\beta$  and charged Higgs boson mass 500 GeV, 1000 GeV and 2000 GeV as benchmark points.

We generate the signal samples of the process  $pp \rightarrow h^- t + X$  followed by the decay mode  $h^- \rightarrow b\bar{t}$  leading to an intermediate state of a pair of top quarks and a  $b$ -quark. We use Pythia 8 package [17] for the signal event generation, where the subprocess

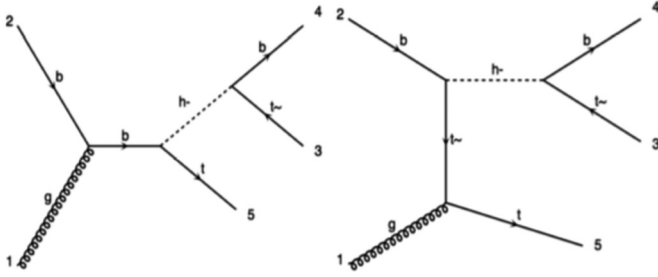


Fig. 1. Feynman diagrams for subprocess  $gb \rightarrow h^- t \rightarrow b \bar{t}$ .

$gb \rightarrow h^- t$  already exists in this 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 type of fermion particles ( $f_i$ ) and  $b$ -jets ( $b_i$ ) such as  $f_1 f_2 f_3 f_4 b_1 b_2 b_3$ . All hadronic mode suffers from large QCD multijet background. The analysis of the leptonic channels has an advantage of being more cleaner when compared to all hadronic mode. However, dilepton channel has low branching ratio leading to lower statistics when compared to the single lepton channel. We also expect better detection prospects in the single lepton mode, based on the results from the searches at the LHC. 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) [16] for different model parameters: mass ( $m_{h^-} \equiv m_{H^0}$ ) in the range of (500 – 2000) GeV, ratio of the vacuum expectation values ( $\tan\beta$ ) in the range of (1 – 30), and a parameter  $\cos(\beta - \alpha) \simeq 0$  (alignment limit) which is relevant for  $H^0 V V$ ,  $h^0 A Z$  and  $h^0 h^\pm W^\mp$  couplings. However, the background Les Houches events (LHE) are generated with MadGraph 5 [18]. 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 [19] for parametric card (FCChh.tcl) of an FCC-hh detector. Event selection is applied on those samples with Heppy [20]. 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 [21] tree.

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

### 3. 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  $\cos(\beta - \alpha) \simeq 0$ . 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 analyzed 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 Fig. 3 for the signal events with mass  $m_{h^-} = 1000$  GeV and  $m_{h^-} = 2000$  GeV, respectively. In Fig. 4 and Fig. 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 sub-leading  $b$ -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 they 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

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

Number of signal and background events and statistical significance for the integrated luminosity of  $L_{int} = 1 \text{ ab}^{-1}$  (initial),  $L_{int} = 3 \text{ ab}^{-1}$  (for comparison with HL-LHC) and  $L_{int} = 30 \text{ ab}^{-1}$  (ultimate) at FCC-hh are given in Table IV. With an integrated luminosity of  $L_{int} = 3 \text{ ab}^{-1}$  at the HL-LHC, the discovery regions can also be constrained in the associated channel for moderate  $\tan\beta$  up to about 1.5 TeV, however an exclusion limit can be extended for only lower and higher  $\tan\beta$ , which have already been presented in Ref. [15].

### 4. 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-hh collider. The single production of charged Higgs boson through  $pp \rightarrow h^- t + X$  process has been investigated in the mass range 500 GeV to 2000 GeV using multi-jets (at least 5 jets) final states with one electron or muon and missing transverse momentum. Using the relevant SM backgrounds from the lepton+jets final states, we obtain a significant coverage of the signal parameter space and distinguish the charged Higgs boson-top-bottom interaction for the benchmark mass values of 500 GeV, 1000 GeV and 2000 GeV for parameter range from  $\tan\beta = 1$  to  $\tan\beta = 30$  at an integrated luminosity of  $30 \text{ ab}^{-1}$ . Other possible extensions of the Higgs sector can also be searched for a wide range of parameter space in high energy proton-proton collisions at the FCC-hh.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

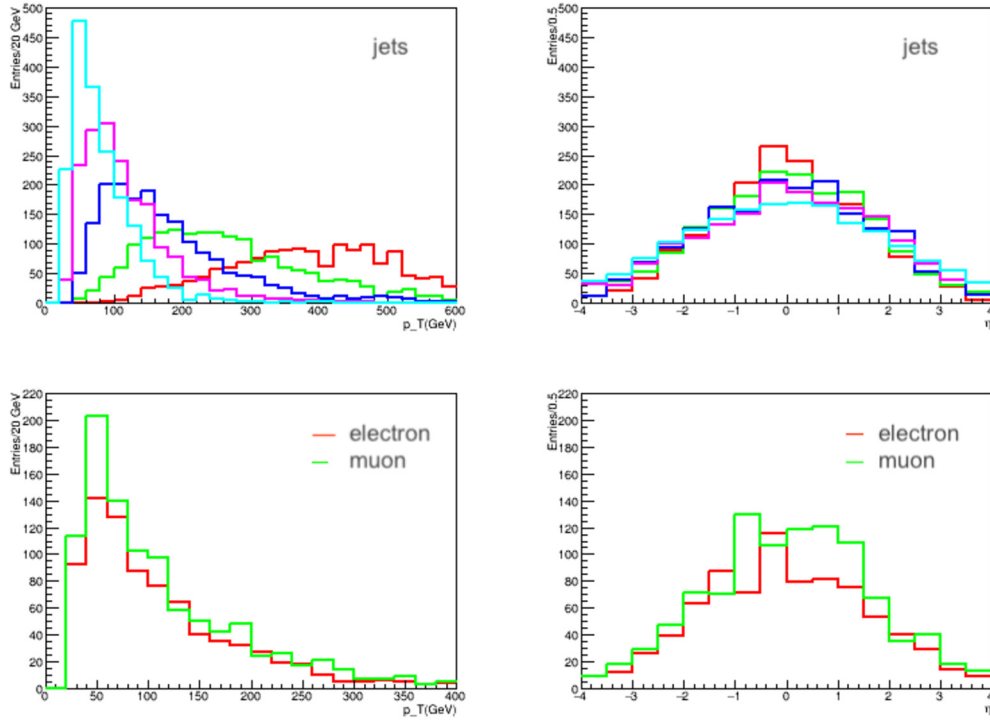


Fig. 2. Transverse momentum and rapidity distributions of final state detectable objects (jets, electron or muon) for signal (mass  $m_{h^-} = 1000$  GeV).

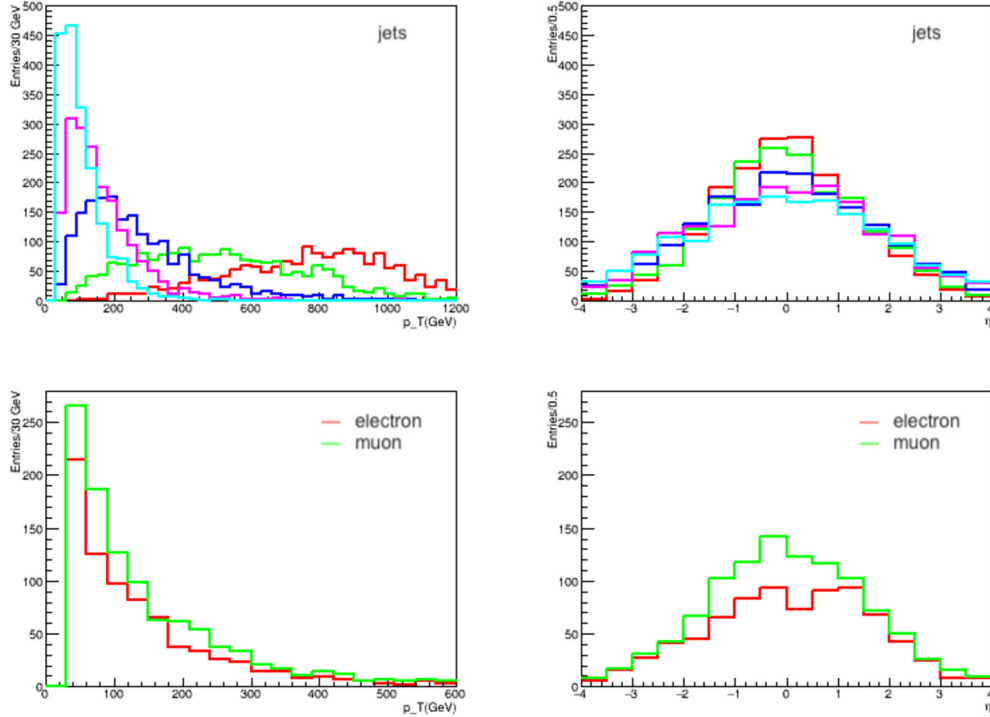


Fig. 3. The same as Fig. 2, but for the charged Higgs boson mass  $m_{h^-} = 2000$  GeV.

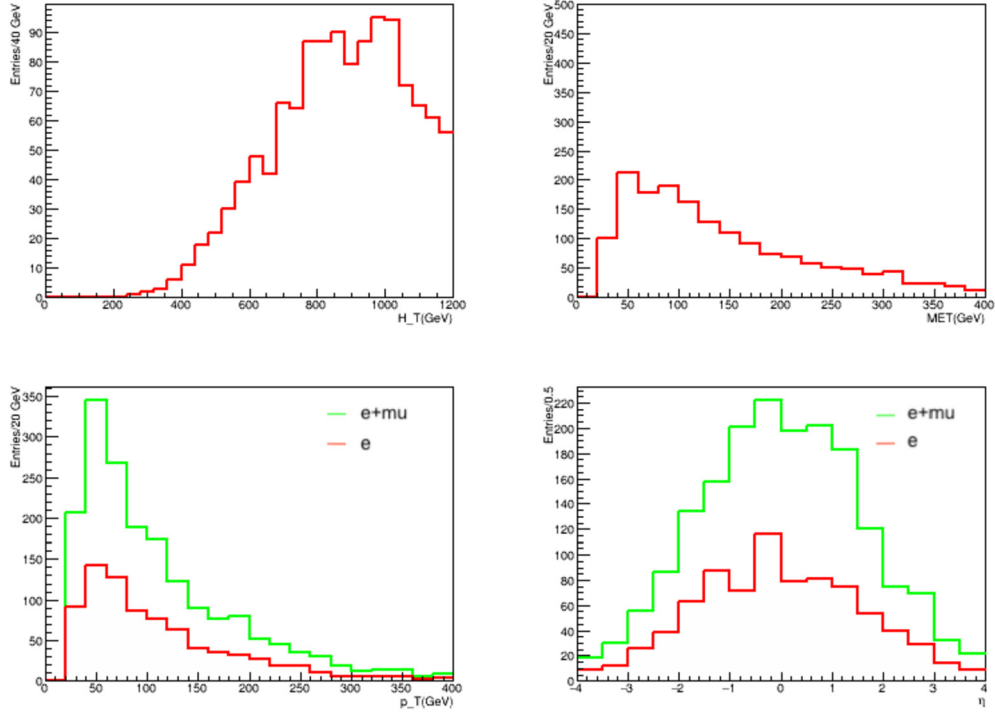
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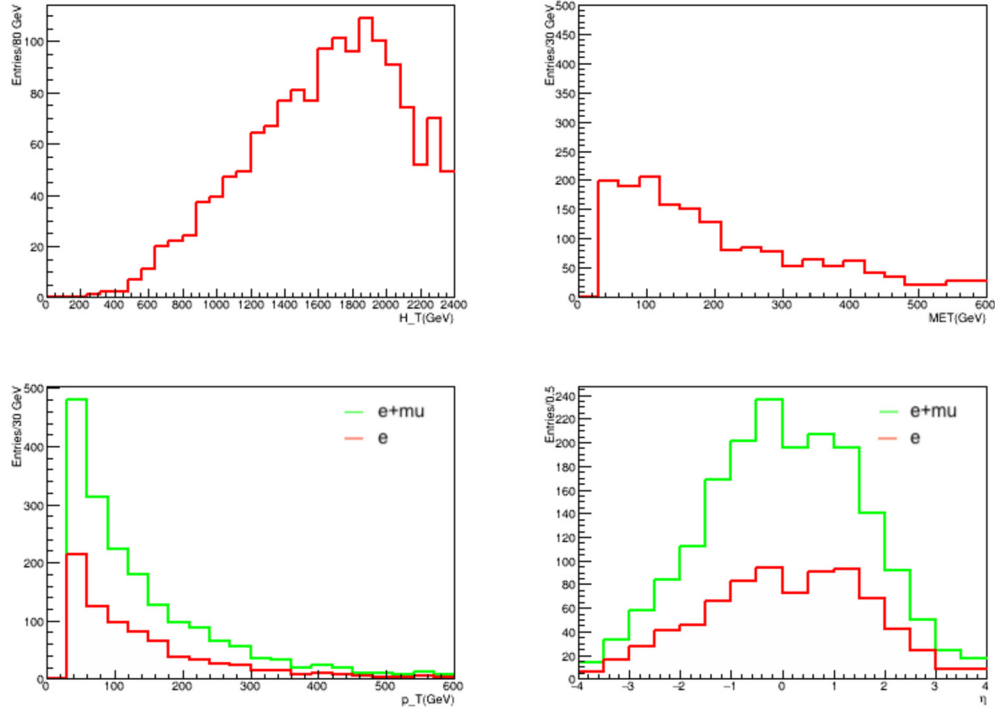
### Appendix

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

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



**Fig. 4.** Hadronic transverse energy ( $H_T$ ) for jets, missing transverse energy (MET) and lepton (e and e+mu) kinematical distributions ( $p_T$  and  $\eta$ ) for signal (with mass  $m_{h^-} = 1000$  GeV).



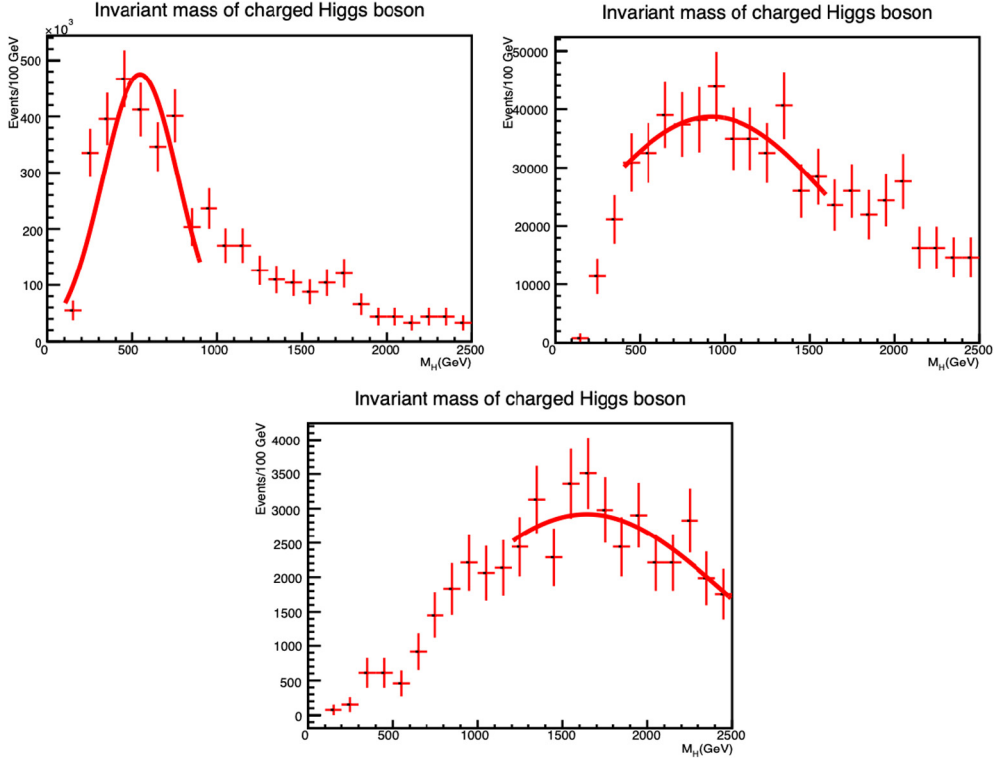
**Fig. 5.** The same as Fig. 4, but for the mass  $m_{h^-} = 2000$  GeV.

$$\begin{aligned}
 & + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2) \Big] \\
 A_2(\hat{s}) &= -4m_b^2 m_t^2 (m_b^2 + \hat{s}) \\
 A_3(\hat{s}, \hat{t}, m_{h^-}) &= m_b^2 \left[ m_b^4 + m_b^2(3m_{h^-}^2 - 2m_t^2 - 4\hat{s} - \hat{t}) \right. \\
 & \left. + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2) \right] \\
 A_4(\hat{s}, \hat{t}, m_{h^-}) &= 2m_t^2 \left[ m_b^4 - m_t^4 + m_t^2 \hat{s} \right. \\
 & \quad + \hat{s}^2 + m_{h^-}^2 (m_t^2 - \hat{s} - \hat{t}) \\
 & \quad + m_b^2 (3m_{h^-}^2 - 3(\hat{s} + m_t^2) - \hat{t}) \\
 & \quad \left. + (m_t^2 + \hat{s})\hat{t} \right] \\
 A_5(\hat{t}, m_{h^-}) &= 4m_b^2 m_t^2 (-2m_b^2 + m_{h^-}^2 - 2m_t^2 + \hat{t})
 \end{aligned} \tag{6}$$

**Table II**

Signal cross sections (in pb) depending on different mass values and parameter  $\tan\beta$ , and the relevant background cross sections at FCC-hh.

Cross sections (pb)	$\tan\beta = 1$	$\tan\beta = 7$	$\tan\beta = 10$	$\tan\beta = 30$
$m_{h^-} = 500$ GeV	$5.495 \times 10^1$	$1.837 \times 10^0$	$2.027 \times 10^0$	$1.344 \times 10^1$
$m_{h^-} = 1000$ GeV	$8.129 \times 10^0$	$2.728 \times 10^{-1}$	$2.981 \times 10^{-1}$	$1.934 \times 10^0$
$m_{h^-} = 2000$ GeV	$7.634 \times 10^{-1}$	$2.558 \times 10^{-2}$	$2.795 \times 10^{-2}$	$1.778 \times 10^{-1}$
Process		$pp \rightarrow t\bar{t}$	$pp \rightarrow t\bar{t}j$	$pp \rightarrow t\bar{t}b$
Background cross sections (pb)		$2.607 \times 10^4$	$4.037 \times 10^4$	$4.906 \times 10^2$



**Fig. 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 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 $p_T$	$\cancel{p}_T > 30$ 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 $t$ mass range	$130 < m_{Wb} < 200$ GeV
Reco $h^-$ mass range	$ m_{tb} - m_{h^-}  < 0.4m_{h^-}$

**Table IV**

Number of signal ( $N_S$ ) and background ( $N_B$ ) events within the  $\Delta m = \pm 0.4m_{h^-}$  interval and statistical significance ( $SS$ ) for the integrated luminosity of  $L_{int} = 1$  ab $^{-1}$ ,  $L_{int} = 3$  ab $^{-1}$  and  $L_{int} = 30$  ab $^{-1}$  at FCC-hh.

Mass (GeV)	$N_B(\Delta m)$	$\tan\beta$	$N_S(\Delta m)$	$SS(1)$	$SS(3)$	$SS(30)$
500	368662140	1	2851903	148.34	256.93	812.49
		7	95340	4.96	8.59	27.17
		10	105201	5.47	9.47	29.96
		30	697536	36.32	62.91	198.93
1000	234516253	1	327598	21.38	37.03	117.10
		7	10993	0.720	1.25	3.94
		10	12013	0.780	1.35	4.27
		30	77940	5.08	8.79	27.82
2000	61585260	1	22825	2.91	5.04	15.94
		7	764	0.097	0.168	0.531
		10	835	0.106	0.183	0.580
		30	5316	0.677	1.17	3.71

$$A_6(\hat{s}, \hat{t}, m_{h^-}) = 2m_b^2 \left[ m_b^4 - m_t^4 + m_t^2 \hat{s} + \hat{s}^2 + m_{h^-}^2 (m_t^2 - \hat{s} - \hat{t}) \right] + m_b^2 (3m_{h^-}^2 - 3(m_t^2 + \hat{s}) - \hat{t}) + (m_t^2 + \hat{s})\hat{t}$$

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

$$(7) \quad A_8(\hat{s}, \hat{t}, m_{h^-}) = -4m_b^2 m_t^2 (m_b^2 + m_{h^-}^2 + 2m_t^2 - \hat{s} - \hat{t})$$

$$A_9(\hat{s}, \hat{t}, m_{h^-}) = m_b^2 \left[ m_b^4 - 2m_t^4 + m_b^2 (m_{h^-}^2 - 4m_t^2 - 2\hat{s} - \hat{t}) + 2m_t^2 (\hat{s} + \hat{t}) + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2) \right] \quad (8)$$

when the mass of  $b$ -quark ( $m_b$ ) is neglected, these terms reduce to a simplified form of coefficients  $A_1(\hat{s}, \hat{t}, m_{h^-}) = m_t^2 [\hat{s}(\hat{s} + \hat{t} - m_{h^-}^2)]$ ,  $A_4(\hat{s}, \hat{t}, m_{h^-}) = 2m_t^2 [-m_t^4 + m_t^2 \hat{s} + \hat{s}^2 + m_{h^-}^2 (m_t^2 - \hat{s} - \hat{t}) + \hat{t}(\hat{s} + m_t^2)]$ ,  $A_7(\hat{s}, \hat{t}, m_{h^-}) = m_t^2 [-2m_t^4 + 2m_t^2(\hat{s} + \hat{t}) + \hat{s}(\hat{s} + \hat{t} - m_{h^-}^2)]$ , and all other coefficients vanish. In this case hadronic cross section  $\sigma(s, m_{h^-})$  will be proportional to  $1/\tan^2 \beta$  as mentioned in the text.

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