Charged Higgs observability via charged Higgs pair production at future lepton collider

Nadia Kausar, Ijaz Ahmed, M. W. Ather

1 Riphah International University, Sector I-14, Hajj Complex, Islamabad, Pakistan
2 National University of Technology, Islamabad, Pakistan

Received: 10 February 2022 / Accepted: 9 May 2022
© The Author(s), under exclusive licence to Società Italiana di Fisica and Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract The observability of charged Higgs bosons $H^\pm$ has been investigated at future lepton collider in type I two-Higgs-doublet model (2HDM) at the center of mass energy $\sqrt{s} = 1.5\text{TeV}$. The signal process chain is $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow H^+ H^- \rightarrow HW^+ HW^- \rightarrow b\bar{b} j j b\bar{b} j j$. The process proceeds through virtual $\gamma$ and $Z$ boson exchange in the $s$ channel. Several benchmark points are selected, and events are analyzed to reconstruct the mass of charged Higgs bosons $H^\pm$. The value of $\tan \beta$ is kept relatively high to enhance the branching ratio of $H \rightarrow b\bar{b}$ to benefit the signal processes. The main standard model (SM) background process produced is $t\bar{t}$. Signal selection and significance efficiencies are calculated at integrated luminosities of $100 \text{ fb}^{-1}$, $500 \text{ fb}^{-1}$, $1000 \text{ fb}^{-1}$, and $5000 \text{ fb}^{-1}$. The reconstructed and corrected mass of charged Higgs bosons $H^\pm$ is determined. Analyzing the results demonstrates that charged Higgs bosons can be discovered through the pair production process via its bosonic decays. This study is supposed to provide the experimentalists with a good way to examine the Higgs bosons beyond SM and to check the validity of 2HDM models in considered parameter space.

1 Introduction

The fundamental particle constituents of matter and their interactions are the focus of elementary particle physics [1]. The standard model (SM) of particle physics has been tested experimentally over the last few decades, with excellent agreement between theoretical predictions and experimental data. The gauge boson and fermion sectors of the standard model of electroweak interactions have been extensively phenomenologically investigated; however, its scalar sector has yet to be directly explored. The SM assumes the simplest possible scalar structure with just one doublet. The Higgs mechanism is thought to be the best way to give masses to massless electroweak particles and gauge bosons [2–7]. Standard model extension [8] contains more than one Higgs doublet and predicts Higgs bosons that could be lighter than the standard model one and accessible at LEP. Models with two complex Higgs massless electroweak particles and gauge bosons [2–7]. Standard model extension [8] contains more than one Higgs doublet and predicts Higgs bosons that could be lighter than the standard model one and accessible at LEP. Models with two complex Higgs doublets, in particular, predict two charged Higgs bosons $H^\pm$ which can be produced in $e^+e^-$ collisions. Several extensions of the SM predict a more complex Higgs sector with multiple Higgs fields, resulting in a spectrum of Higgs bosons with varying masses, charges, and other properties. The measured properties of the 125 GeV boson constrain, but do not exclude, these models. The discovery of additional Higgs bosons would provide unequivocal proof of the existence of physics beyond the standard model. The two-Higgs-doublet model (2HDM) predicts five distinct Higgs bosons, two neutral charge parity (CP) even bosons $h$ and $H$ (with $m_h \leq m_H$), one neutral CP odd boson $A$, and two charged Higgs bosons $H^\pm$ [9]. The 2HDM provides a well-motivated class of models that are compatible with the Higgs discovery by extending the SM Higgs sector using two doublets [10–13].

The discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 confirmed that the Higgs mechanism is the correct approach. This discovery sets off a race among scientists to determine whether there is only one observed Higgs or whether multiple Higgs states are also possible, as predicted by various extended theories. LEP2 and the LHC are conducting searches for charged Higgs $H^+$ of the 2HDM (Model I). The search for $H^+ H^-$ pairs was conducted using 175 pb$^{-1}$ of ALEPH data collected at $\sqrt{s} = 189$ in four jet channels [14]. Furthermore, work was done on searches for charged Higgs bosons, and the LEP experiments published their final results on these searches, as well as searches for new final states not previously considered, in 2001 [15]. The four LEP collaborations looked for charged Higgs bosons as well. Based on the final results of ALEPH [16,17], DELPHI [18], L3 [19,20], and OPAL [21], a statistical combination of the data was taken at center of mass energies ranging from 183 GeV to 209 GeV. The total luminosity for this combination is 2.6 fb$^{-1}$. Using DELPHI and OPAL analyses in the bosonic $W A$ decay channels, the masses of the charged Higgs boson less than 72.5 GeV/c$^2$ and for $A$ boson greater than 12 GeV/c$^2$ were excluded at the 95%
confidence level (CL) [22]. If the charged Higgs boson decays primarily to $\tau \nu$ or $c\bar{s}$, the LEP II lower bound on the mass is around 80 GeV, whereas if the charged Higgs decays primarily to $W^\pm A$, via a light CP odd Higgs state $m_A = 12$ GeV, the lower bound on the mass is around 72 GeV [23].

The main search mode at the LHC was the production via the decay of the top quark, followed by the decay of $H^\pm$ into $\tau \nu$. Both the ATLAS and CMS collaborations looked into this mode [24–26]. The charged Higgs search has been carried out at colliders such as LEP [27], Tevatron [28], and LHC using the ATLAS [29–32] and CMS [33,34] experiments. Exclusion limits for LEP experiments were set at $m_{H^\pm} > 79.3$ GeV at 95% CL, independent of branching ratios (BR) [35], assuming $BR(c\bar{s}) + BR(\tau \nu) = 1$. For the low charged Higgs mass, the set limit is 87.8 GeV if $BR(\tau \nu) = 1$. The is a set of range for BR, cross section and masses of $H^\pm$ in ATLAS at 95% CL. The BR ($t \to H^\pm b$) is in the range $(0.23 - 1.3)\%$. For the charged Higgs mass the range is 80 GeV < $m_{H^\pm}$ < 160 GeV, and the production cross section is in the range 0.0045 – 0.76 pb for the mass range 180 GeV < $m_{H^\pm}$ < 1000 GeV, both with the assumption that BR($H \to \tau \nu$) = 1 [32]. Similarly, the upper limits on BR ($t \to H^\pm b$) for the mass range 80 GeV < $m_{H^\pm}$ < 160 GeV are set in the range $(0.16 - 1.2)\%$, and for the mass range 180 GeV < $m_{H^\pm}$ < 600 GeV, the upper limits on the production cross section of charged Higgs are set in the range 0.026 – 0.38 pb in CMS experiment at 95% CL [34]. The LHC search for charged Higgs bosons has also been investigated in [36–40].

Because the chosen parameters are based on processes produced by collisions between lepton beams, the chosen benchmark points may not simply apply to the same process produced by hadronic beams. When compared to lepton colliders, the hadron machine produces multiple QCD jets with several times more multiplicity. As in the case of background events, this results in more several QCD backgrounds with similar final state particles. As a result, the kinematical cuts and search strategy will be significantly different. The Lepton collider only contains QED processes, which are easily manageable even with traditional selection cuts.

Compact Linear Collider (CLIC) is one of the proposed future lepton colliders to accelerate the electron and positron beams. CLIC is aimed to be constructed and operated in three steps, i.e., at 380 GeV, 1.5 TeV and 3 TeV collision energies, respectively. Lepton collider can measure the Higgs couplings with more precision than already achieved by LHC. It is thought that due to its clean environment, CLIC is more capable of finding new physics which is why in this study, the phenomenology for this collider is made [41]. The aim of designing CLIC is to achieve the electron positron head on, collisions at several tera electron volts (TeV) energies.

The focus of the paper is on the study of charged Higgs pair bosons $H^{\pm}$ and their bosonic decays. The theoretical framework for this work is type I, 2HDM. The study of the observability of charged Higgs bosons $H^{\pm}$ takes place by the signal process $e^+e^- \to Z^*/\gamma^* \to H^+H^- \to HW^+HW^- \to b\bar{b}jjb\bar{b}jj$, where $j$ represents light jet and $b$ is the bottom quark. This is the most favorable production scenario with bosonic decays for charged Higgs study at linear colliders. The process will proceed by exchange of $\gamma$ and $Z$ boson in the $s$ channel. Figure 1 shows the Feynman diagram of this process. In this analysis, each of the charged Higgs decays into $W^\pm H$ and the final state becomes $2W^\pm H$. Several benchmark points in the parameter space of 2HDM [42] are considered for charged Higgs bosons observability at the center of mass energy $\sqrt{s} = 1.5$ TeV. The signal and background events are generated independently for each scenario [43]. The charged Higgs boson candidates are identified by comparing the signal with background events in different distributions. To reconstruct the charged Higgs bosons, simulated events are analyzed. For this purpose, first of all the $b$ jets are identified. These $b$ jets are reconstructed by choosing proper $b$ tagging algorithms and $b$ jet clustering. The combinations of $b$ jets are identified so that the di-jet invariant mass gives us the Higgs candidate. The mass range for studied charged Higgs is 125 GeV < $m_{H^{\pm}}$ < 400 GeV at $\sqrt{s} = 1.5$ TeV at the integrated luminosity of 500 fb$^{-1}$.
2 Two-Higgs-doublet model

There are four types of 2HDM. In type I, the gauge bosons and all fermions attain mass from one Higgs doublet while the contribution of the other Higgs doublet is via mixing [44]. Discrete symmetry $\phi_1 \rightarrow -\phi_1$ is involved in type I. One Higgs doublet (conventionally $\phi_2$) couples with all quarks (up type quark and down type quark) and charged leptons in type I, 2HDM and the flavor is conserved naturally. There are two discrete situations to achieve natural flavor conservation in 2HDM. First, when only one Higgs doublet (conventionally $\phi_2$) couples with all quarks (up type and down type) and charged leptons, it is named the type I, 2HDM. In the second case, termed as type II, 2HDM all the up type quarks couple to one Higgs doublet ($\phi_2$), and all down type quarks along with charged leptons couple with the other Higgs doublet ($\phi_1$). It can be observed that a discrete symmetry ($\phi_1 \rightarrow -\phi_1$) can be implemented on type I, 2HDM. It is conventionally assumed that the up type quarks are always coupled with the second doublet $\phi_2$ in all types. The charged Higgs phenomenology is strongly influenced by the type of Yukawa sector. Since all couplings of the $H^+$ to quarks in type I (and type X) are proportional to cot $\beta$, it is proportional to $\sin(\alpha - \beta)$ in the case of bosonic decays. With increasing tan $\beta$ values, the production cross section decreases. This is in contrast to the MSSM, which has a Model II structure and a cross-section with a minimum for intermediate tan $\beta$ values of the order of $\sqrt{m_t/m_b}$ [45]. In the intermediate mass region, Model II and Model Y are excluded by the $B \rightarrow X_s \gamma$. Due to measurements of the inclusive weak radiative decay $B \rightarrow X_s \gamma$, the charged Higgs boson in type II, and type Y is tightly constrained to be as heavy as $m_H^+ \gtrsim 580$ GeV [26,46]. The only type I, and type X can support a light $H^\pm$. Different types of 2HDM are shown in Table 1. The expression for the general scalar potential with two Higgs doublets $\phi_1$ and $\phi_2$ can be written as

$$V_{2HDM} = \frac{m_{11}^2}{2} \phi_1^\dagger \phi_1 + \frac{m_{22}^2}{2} \phi_2^\dagger \phi_2 - \frac{m_{12}^2}{2} \phi_1^\dagger \phi_2 + \text{h.c}$$

$$+ \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2$$

$$+ \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)$$

$$+ \left[ \frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)^2 + [\lambda_6 (\phi_1^\dagger \phi_1)$$

$$+ \lambda_7 (\phi_2^\dagger \phi_2)](\phi_1^\dagger \phi_2) + \text{h.c} \right]$$

(1)

In Eq. (1), $\lambda_i$, where ($i = 1, 2, \ldots, 7$) are coupling parameters having no dimensions, and $m_{11}^2$, $m_{22}^2$, and $m_{12}^2$ are squared mass parameters. Out of these parameters the $m_{12}^2$ and $\lambda_i$ (Where $i = 5, 6, 7$) are preferably complex while the remaining parameters are real. The $m_{12}^2$ term is of great importance because its nonzero values cause the soft breakdown of the $Z_2$ symmetry ($\phi_1 \rightarrow -\phi_1$) or ($\phi_2 \rightarrow \phi_2$). The potential becomes explicitly CP-violating in the presence of nonzero imaginary parts of the complex parameters therefore to treat the potential as CP conserving here it is supposed that all the parameters used are real. For a complete specification of the model, the different parameters $m_{12}^2$, tan $\beta$, physical Higgs masses $m_{H^\pm}$, $m_A$, $m_h$, mixing angle $\alpha$, $\sin(\beta - \alpha)$, $\lambda_5$ and $\lambda_7$ must be calculated in the physical basis [9,47]. If the value of $\sin(\beta - \alpha)$ is taken to be one, then it is called the exact alignment limit in which the lighter CP even Higgs $h$ behaves like SM Higgs boson and if the value of $\sin(\beta - \alpha)$ is taken to be zero then the heavier CP even Higgs boson behaves like SM Higgs boson. This study is performed within alignment limit, i.e., $\sin(\beta - \alpha) = 1$. The mass of lighter Higgs is taken as the mass of SM Higgs boson, i.e., $m_h = 125$ GeV. In type I, 2HDM all the fermions couple with a single Higgs doublet ($\phi_2$) same as in SM; however, the other Higgs doublet does not couple at all. This is due to the implementation of distinct $Z_2$ symmetry. For Yukawa interactions in type I, 2HDM the Lagrangian is given in Eq. (2)

$$L_{\text{Yukawa}} = Y_e \overline{L} \phi_2 e_R + Y_u \overline{Q} \phi_2 u_R + Y_d \overline{Q} \phi_2 \phi_2 d_R + \text{h.c}$$

(2)

where $e_R$, $u_R$, and $d_R$ are the left handed leptons, up type, and down type quarks singlet, respectively, with $Y_e$, $Y_u$, and $Y_d$ as their corresponding Yukawa coupling matrices. The terms $\overline{L}$ and $\overline{Q}$ are left-handed lepton and quark doublets, respectively, and

| Types of model | Description | $u_R^i$ | $d_R^i$ | $e_R^i$ |
|---------------|-------------|---------|---------|---------|
| Type I        | Fermiophobic| $\phi_2$| $\phi_2$| $\phi_2$|
| Type II       | MSSM like   | $\phi_2$| $\phi_1$| $\phi_1$|
| Type III      | Lepton-specific| $\phi_2$| $\phi_2$| $\phi_1$|
| Type IV       | Flipped     | $\phi_2$| $\phi_1$| $\phi_2$|
both processes vanish when the requirement is like SM [43]. The final states in LHC charged Higgs searches are the decaying charged Higgs in the presence of a new, competing charged Higgs decay, namely either $\pm \rightarrow W^\pm Z$ or $\pm \rightarrow W^\pm H$. These parameter space regions within the 2HDM type I are amenable to immediate experimental investigation by the ATLAS and CMS collaborations, which have so far focused almost exclusively on $t\tau$ production and decay [51]. The possibility of a light charged, Higgs is investigated. The charged Higgs is produced in top decay via the single top or top pair production, which is the most common way for a light charged

$$\hat{\phi}_2 = i\sigma_2 \phi_2^*$$ (where $\sigma_2$ is Pauli matrix). If the weak eigenstates of $\phi_2$ are expressed in physical terms then Eq. (2) becomes

$$L_{\text{Yukawa}} = - \left\{ \sum_{\psi=u,d,l} \frac{m_\psi}{\sqrt{2}v} (\kappa_\psi^W \bar{\psi} W^+ \psi H^0 + \kappa_\psi^H \bar{\psi} H^0 - \kappa_\psi^{\tilde{H}} \bar{\psi} \tilde{H} \gamma \phi A) \right\}$$

In Eq. (3) the $\kappa$ factors represent the Yukawa couplings and their values for 2HDM type I are given in Table 2. For all types of 2HDM, $W$ and $Z$ boson couplings with neutral Higgs bosons are identical. Light Higgs $h$ and heavy Higgs $H$ couplings with either $ZZ$ or $WW$ are equal to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ times the corresponding standard model couplings, respectively. The coupling for the interaction between the Higgs boson pair and gauge boson like $H^\pm W^\mp H$ can be estimated by using the gauge coupling structure and the angles $\alpha$ and $\beta$. The coupling relations [48] are given in Eqs. (4), (5), and (6).

$$g(H^\pm H W^\mp) = \frac{g}{2} (p_H - p_{H^\pm})^\mu \sin(\beta - \alpha)$$

$$g(H^\pm h W^\mp) = \frac{g}{2} (p_h - p_{H^\pm})^\mu \cos(\beta - \alpha)$$

$$g(H^\pm A W^\mp) = \frac{g}{2} (p_A - p_{H^\pm})^\mu$$

where $p_H$, $p_h$ and $p_A$ represent the momentum of incoming particles, respectively.

### 3 Strategy and signal extraction

In this study, events are produced with the help of Pythia-8210 [49] and relative efficiencies are also calculated in it. 2HDMC-1.7.0 [50] is used to calculate the branching ratios as well as decay widths of the Higgs sector in type I, 2HDM at desired benchmark points and its output in SLHA format is fed to Pythia. For the analysis and reconstruction of jets produced in the events, Pythia is linked with fastjet-3.3.3. To record the events data, the interface of HepMC-2.06.06 [51] is given to Pythia. The output of Pythia is then analyzed and histograms are plotted by using Root-6.20/04 [52].

#### 3.1 Signal process

The observability of the charged Higgs bosons is investigated through the signal process $e^+e^- \rightarrow H^+H^-$. The process chain is $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow H^+H^- \rightarrow HW^+HW^- \rightarrow b\bar{b}j j b\bar{b}j j$. There are many other possibilities for this process. In the process $e^+e^- \rightarrow Zh$, $h$ has taken as SM Higgs, so it cannot be taken for study when Higgs boson beyond SM is studied. In processes $e^+e^- \rightarrow ZH$ or $e^+e^- \rightarrow Ah$, the $ZZ$ and $hZA$ vertices are involved and both are proportional to $\cos(\beta - \alpha)$. At $\sin(\beta - \alpha) = 1$, both processes vanish when the requirement is like SM [43]. The final states in LHC charged Higgs searches are $\tau\nu$ and $tb$ from the decaying charged Higgs in the presence of a new, competing charged Higgs decay, namely either $H^\pm \rightarrow W^\pm A$ (with a light pseudoscalar Higgs $A$) and/or $H^\pm \rightarrow W^\pm H$ (with a light, non standard Higgs boson $H$). These findings justify a dedicated LHC search program for the process $H^\pm \rightarrow W^\pm H$, with the charged Higgs boson $H$ produced either in the top quark decays or directly in association with a top and bottom quark, and the neutral Higgs boson $H$ decaying into either $bb$ or $\tau\tau$. Such investigations would result in significant and complementary constraints on the charged Higgs sector of the 2HDM [47]. In another process the charged Higgs $H^\pm$ decays into $W^{(*)}h$ (with $h$ being the SM like Higgs state) and/or, especially, $W^{(*)}h$ in which the $m_{H^\pm} < m_t - m_h$. The production of $H^\pm$ in a single-mode from the decay of (anti)top quark is possible at high rates, which are potentially accessible during the current LHC Run 2. These parameter space regions within the 2HDM type I are amenable to immediate experimental investigation by the ATLAS and CMS collaborations, which have so far focused almost exclusively on $\tau\nu$ and/or $cs$ decays of light charged Higgs state emerging from $t\bar{t}$ production and decay [53]. The possibility of a light charged, Higgs is investigated. The charged Higgs is produced in top decay via the single top or top pair production, which is the most common way for a light charged

| $\kappa_u^h$ | $\kappa_d^h$ | $\kappa_l^h$ | $\kappa_u^H$ | $\kappa_d^H$ | $\kappa_l^H$ | $\kappa_u^A$ | $\kappa_d^A$ | $\kappa_l^A$ |
|------------|------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $\cos \alpha$ | $\cos \alpha$ | $\sin \beta$ | $\sin \alpha$ | $\sin \alpha$ | $\sin \beta$ | $\cot \beta$ | $-\cot \beta$ | $-\cot \beta$ |
| $\sin \beta$ | $\sin \beta$ | $\cos \alpha$ | $\sin \alpha$ | $\sin \alpha$ | $\sin \beta$ | $\cot \beta$ | $-\cot \beta$ | $-\cot \beta$ |

### Table 2 Values of Yukawa couplings for 2HDM type I

3.1 Signal process
Higgs to be produced at the LHC. The subsequent decay $H^\pm \to AW/HW$ is considered. If this decay is kinematically permitted, then a significant branching fraction is obtained at the low value of $\tan \beta$ [54]. At the LHC and the Tevatron, researchers are looking for light charged Higgs bosons $H$ in the decay of top quarks, $t \to H^\pm b$. The dominant decay channels for such $H^\pm$ state are either $H^\pm \to \tau \nu$ or $H^\pm \to cs$, and separate searches are performed with comparable sensitivity to the scalar potential parameters $m_{H^\pm}$ and $\tan \beta$ [55]. In another process, there are three different decays of charged Higgs $H^\pm \to hW^* \to hf^+f^-$, $H^\pm \to AW^* \to Af^+f^-$ and $H^\pm \to \bar{b}l^* \to b\bar{b}W$ [56]. The decays of charged Higgs $H^\pm \to HW$ and $H^\pm \to AW$ for other channels are also given in [26,57–60]. The choice of process $e^+e^- \to Z^*/\gamma^* \to H^+H^-$ is most suitable and favorable for the study of charged Higgs at the linear collider. The process takes place through the exchange of $y$ and $Z$ bosons in the $s$ channel. Each heavy neutral Higgs boson $H$ is allowed to disintegrate only into two $b$ jets and the $W$ boson is allowed to decay into two light jets. The final state contains four $b$ jets, and four light jets.

In this study, the masses of charged Higgs $H^\pm$ and pseudoscalar Higgs $A$ are considered the same in order to avoid the decay of charged Higgs bosons into pseudoscalar Higgs $A$. The selected benchmark points which fulfill the theoretical and experimental constraints are considered. The 2HDMC-1.7.0 [61] is linked with packages HiggsBound-4.2.0 and HiggsSignal-1.4.0. It is used to make sure that all the benchmark points are consistent with all experimental and theoretical constraints. The range of parameter $m_{T_2}$ for each benchmark point satisfies the theoretical constraints. The mass splitting between the heavy neutral Higgs and charged Higgs is taken in such a way that the bosonic decay of both charged Higgs $H^\pm \to W^\pm H$ is kinematically permitted. The ranges of heavy neutral and charged Higgs bosons, $\tan \beta$, $m_{T_2}$, and $\sin(\beta - \alpha)$ for the different benchmark points are listed in Table 3.

The branching ratios for decays $(H^\pm \to W^\pm H)$ and $(H \to b\bar{b})$ as well as decay widths of Higgs sector is obtained by using 2HDMC-1.7.0 [61] for the selected benchmark points and are given in Table 4. All this information about a benchmark point is also included in its Susy Le Houches (SLHA) file and is provided to Pythia8210 [49] as input for generating events. The cross section for the process at given benchmark points is calculated by using Comphep-4.5.2 [62,63] and is shown in Table 5. Energy is plotted versus cross section as shown in Fig. 2. Figure 2 shows that with the increase in energy, the cross section increases rapidly. It has the maximum value when energy becomes equal to the threshold energy. It is the energy, required to produce the process. The cross section decreases with a further increase in energy, and it almost becomes linear at the $3\,\text{TeV}$. It is due to the reason that the cross section of a process is inversely proportional to the square of the center of mass energy. At the center of mass energy $\sqrt{s}=3\,\text{TeV}$, the cross sections for all benchmark points have the same value, which means that the cross sections become independent of the center of mass energy, and plots at this energy become linear.

The main SM background process in the signal channel is the production of pair of top quark $t\bar{t}$ through electron positron annihilation $e^+e^- \to t\bar{t}$. Events for this background process are also generated in Pythia because all the known information about SM particles, their couplings, and SM processes are already stored in Pythia built in flags.

### Table 3: The Higgs bosons masses, range of $m_{T_2}$ and branching fractions for different benchmark points within the allowed region

| BP  | $m_h$ (GeV) | $m_H$ (GeV) | $m_A$ (GeV) | $m_{H^\pm}$ (GeV) | $\tan \beta$ | $m_{T_2}^2$ (GeV$^2$) | $\sin(\beta - \alpha)$ |
|-----|-------------|-------------|-------------|------------------|--------------|-----------------------|------------------------|
| BP1 | 125         | 125         | 125         | 125              | 40           | 560                   | 1                      |
| BP2 | 150         | 200         | 325         | 400              | 40           | 996–999               | 1                      |
| BP3 | 250         | 325         | 400         | 400              | 40           | 1560                  | 1                      |
| BP4 | 250         | 325         | 400         | 400              | 40           | 2245–2248             | 1                      |

### Table 4: The branching ratios at each benchmark points

| BP  | $BR(H^\pm \to W^\pm H)$ | $BR(H \to b\bar{b})$ |
|-----|--------------------------|-----------------------|
| BP1 | $9.89 \times 10^{-1}$    | $7.112 \times 10^{-1}$ |
| BP2 | $9.95 \times 10^{-1}$    | $6.16 \times 10^{-1}$  |
| BP3 | $9.97 \times 10^{-1}$    | $5.08 \times 10^{-1}$  |
| BP4 | $9.75 \times 10^{-1}$    | $3.79 \times 10^{-1}$  |

3.2 Event selection process for identification of jets

The generated events are stored in HepMC-2.06.06 [51]. The jets produced in the events are reconstructed by using the FASTJET [64]. In this study anti-$k_t$, jet algorithm [65] is used to reconstruct the jets. Different kinematic selection cuts are applied which
Table 5 The cross section, maximum cross section and corresponding cms energy of $e^+e^- \rightarrow H^+H^-$ at different benchmark points

| BP points | $\sigma$ at 1 TeV (fb) | $\sigma$ at 1.5 TeV (fb) | $\sigma$ at 3 TeV (fb) | $\sigma_{\text{max}}$ (fb) | $\sqrt{s}$ (GeV) |
|-----------|------------------------|--------------------------|----------------------|--------------------------|----------------|}
| BP1       | 17.294                 | 10.978                   | 3.1368               | 21.966                   | 800           |
| BP2       | 11.699                 | 9.5886                   | 3.0445               | 12.977                   | 1040          |
| BP3       | 5.761                  | 7.9288                   | 2.9294               | 8.5611                   | 1250          |
| BP4       | 5.761                  | 7.9288                   | 2.9294               | 8.5611                   | 1250          |

Fig. 2 The cross section versus energy at different benchmark points within the allowed region

arises certain fluctuations in the signal. The selection cuts are applied in such a way that enhances the signal to background ratio while signal events are maintained at an appropriate level. Selection efficiencies are calculated and the importance of the signal is determined by computing signal significance. These cuts define the band of ranges which are invariant quantities, measured in events. It must fulfill the number of several final state particles. These particles are identified in the phase of primary reconstruction using “object identification cuts.” Then the kinematic selection cuts are applied to refine the rejection and selection of background events to finalize the results.

The first step in event selection is the kinematic cut on jets which omit the soft $p_T$ jets and the ones that are in the forward region along the collision beams. For this, we apply the following cuts on transverse momentum and pseudorapidity of jets.

$$p_T^{\text{jet}} > 20 \text{ GeV}, \ |\eta_{\text{jets}}| < 2.5$$

Once we have jets within the desired kinematic range, we split the reconstructed jets by identifying them as light and $b$ tagged jets. To achieve this, we do $\Delta R$ matching of the jets with the generated particles and is defined as

$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$

We identify the jets which are within $\Delta R < 0.4$ of the $b$ quarks in the event as $b$ jets and the ones that are farther away from $b$ quarks as light jets. Once we have identified the jets, we apply the multiplicity cut on the jet. For the $jjjjbb$ channel we require the event to have at least four light jets and at least four $b$ jets. In the analysis, we use the selected light jets ($b$ jets) to find a combination that minimizes the $\chi^2$ defined as follows.

$$\chi^2 = \left( \frac{m_{jj,1} - m_W}{\sigma_{m_W}} \right)^2 + \left( \frac{m_{jj,2} - m_W}{\sigma_{m_W}} \right)^2 + \left( \frac{m_{bb,1} - m_H}{\sigma_{m_H}} \right)^2 + \left( \frac{m_{bb,2} - m_H}{\sigma_{m_H}} \right)^2$$  

where $m_{jj,bb}$ is the dijet mass, $m_W$ is the mass of W boson, and $m_H$ is the mass of the heavy Higgs boson according to the BP taken, and the $\sigma_{m_W,H}$ are the widths of the respective mass distributions. The cut of $\chi^2 < 10$ is applied to select only events with
Table 6  The efficiencies for different selection cuts at different mass hypothesis (CH for charged Higgs)

| Cuts                  | BP1    | BP2    | BP3    | BP4    |
|-----------------------|--------|--------|--------|--------|
| Four lightjets        | 0.1467 | 0.2557 | 0.3278 | 0.3052 |
| Four \(b\) jets       | 0.5666 | 0.6478 | 0.6655 | 0.6544 |
| \(\chi^2\)            | 0.2224 | 0.1737 | 0.1085 | 0.6162 |
| CH \(\chi^2\)        | 0.5027 | 0.4526 | 0.3599 | 0.6767 |
| Total efficiency      | 0.00929 | 0.01302 | 0.00852 | 0.00833 |
| \(\sigma \times B.R.\)| 4.58   | 2.17   | 0.66   | 0.37   |

**Fig. 3** The jet multiplicity for events (signal and background)

> good reconstructed \(W\) and \(H\) bosons. The charged Higgs boson \(H^\pm\) is then reconstructed using the combination of \(W\) and \(H\) which gives the mass nearest to \(H^\pm\) nominal mass according to each BP. After applying different selections cuts, The efficiencies are calculated. For getting more better simulation results, more than a hundred thousand events are generated and analyzed for each selected scenario. Applying all cuts on generated events, relative efficiencies for corresponding selection cuts are calculated. In the end, total signal selection efficiency is also calculated for each benchmark point. The results are shown in Table 6. The signal process has reasonable selection efficiency at all the selected benchmark points. From Table 6 it can be seen that from randomly generated signal events, all the events have four \(b\) jets and light jets. This is because heavy scalar Higgs bosons, in signal processes decay into \(b\) jets, and \(W\) bosons decay into light jets.

**4 Results and discussion**

In the finalized results, the topology of our assumed first signal process contains four \(b\) jets and four light jets. Jet multiplicity distributions of signals processes and different SM backgrounds are shown in Fig. 3. The distribution of \(b\) jets slightly depends on neutral Higgs boson mass in the assumed signal event. The production of \(b\) jets is suppressed kinematically in the production of the Higgs boson, the availability of phase space is smaller due to which it decays to bottom quarks. Transverse energy \(E_T\) of jets for different signal and background processes is shown in Fig. 4. The jet pseudorapidity \(\eta\) for different signal and background processes is shown in Fig. 5.

After extracting the data of \(\Delta R\), the profiling process of \(\Delta R\) is discussed. By the analysis of the plot of \(\Delta R\) shown in Fig. 6, the \(b\) jets can easily be identified by finding the minima of the plot. To identify the \(b\) jets from all sorted jets, those jets are chosen which satisfy \(\Delta R < 0.4\). A jet is identified as a \(b\) jet having the possibility of 70% if it has a resemblance with a \(b\) quark and with a chance of 10% if its resemblance with a \(c\) quark. The above-mentioned values are supposed to the \(b\) tagging efficiency and fake rate successively. As signal comprises on four \(b\) jets from the hadronic decay of each heavy Higgs boson denoted by \(H_1\) and \(H_2\). In Fig. 7 the number of \(b\) jets in signals and background events is shown. After the selection cuts, the only background which can contribute up to a reasonable level is \(t\bar{t}\) having a very small number of events with four \(b\) jets. For signal processes, it can be seen that each one has almost 60–70% four \(b\) jets efficiencies. Other SM backgrounds may exist but they have a very small number of events as compared to the signals. In the signal process, these jets come from the hadronic decay of both \(W\) bosons.
Fig. 4 Transverse energy $E_T$ of jets for different signal along with all background events

Fig. 5 The pseudorapidity $\eta$ of signal along with all background events

Fig. 6 The distribution of $\Delta R$ (jets, quarks) variables used to tag $b$ jets for all signal and background processes
Fig. 7 The $b$ jets multiplicity at different benchmark points in various signals and background events.

Fig. 8 The plots of reconstructed invariant mass of $W_1$.

4.1 Reconstruction of $W$ Bosons

For all scenarios, the reconstructed masses peaks are exactly at 80 GeV which is close to the known mass of the $W$ boson in SM (80.4 GeV). For backgrounds, the number of events with reconstructed $W$ masses is very small as compared to our signals and on normalizing the above graphs, the reconstructed $W$ masses for background processes cannot be seen. The histograms are filled for reconstructed masses of both $W^\pm$ for all benchmark points and are shown in Figs. 8 and 9. The representation for $W^\pm$ in histograms is taken as $W_1$ and $W_2$.

4.2 Reconstruction of heavy neutral scalar Higgs Bosons

The invariant mass of neutral scalar Higgs bosons is reconstructed. In this work, the generation of signal and background, processes are involved which display natural interference and selection techniques where different mass speculations are displayed for Higgs invariant mass remaking.

The process of mass reconstruction of Higgs bosons is considered important to attain the reliable separation between the main assumed signal and the background processes. The peak of the signal resonance is produced by the proper mass variable. Through this process, a large signal will be produced over the background ratio. The pair of $b$ jet comes out from the heavy Higgs boson in the signal events. Due to that fact, the invariant mass of this pair should be lesser and lie within mass casement adjusted by neutral Higgs mass. Mass of the Higgs boson can be calculated by the conventional formula given as

$$m_H = \sqrt{E^2 - p_x^2 - p_y^2 - p_z^2}$$  (10)
Then, for each possible combination, the sum of squared differences between observed and predicted Higgs boson masses is calculated. Then, light jet and $b$ jet pairings that meet the following conditions are chosen.

$$\chi^2_{min} < 10$$

Only those events are selected which have four $b$ jets. In $\eta - \phi$ space, $\Delta R$ is calculated for all probable combinations of $b$ jets pair for each event. The selection cut is introduced to justify that the combination of $b$ jets pair is truly coming from Higgs boson decay so their reconstructed masses should be nearly equal to the input mass of heavy Higgs boson ($m_H$). The small fraction of reconstructed masses not lying in this window is eliminated from the efficiency calculation for each signal. The representation of neutral Higgs bosons is taken as $m_{H_1}$ and $m_{H_2}$. Peak of the signal resonance is produced by the proper mass variable. The reconstructed mass distributions of $H_1$ and $H_2$ for different BPs are shown in Figs. 10 and 11 accordingly. It can be examined that the reconstructed masses from di-$b$ jet using $\chi^2$ method are in agreement with the nominal mass for each BP. Figure 10 shows that the peak of reconstructed mass of $H_1$ for BP1, BP2, BP3, and BP4 is at 151.45, 200.97, 249.97, and 298.4 GeV, respectively. Similarly, Fig. 11 shows that the peak of reconstructed mass of $H_2$ for BP1, BP2, BP3, and BP4 is at 151.83, 200.19, 249.39, and 298.59 GeV, respectively. The reconstructed masses are obtained by fitting a suitable Gaussian function on the distribution curves of $m_{H_1}$ and $m_{H_2}$ and taking their mean values.
The reconstructed invariant mass of the Higgs boson is represented by \( m_{\text{rec}} \), and the actual value of the Higgs boson mass is represented by \( m_{\text{Gen}} \). The generated masses, reconstructed masses, and corrected masses of heavy neutral Higgs bosons for each selected scenario are computed in Tables 7 and 8. From Tables 7 and 8, it can be observed that the reconstructed masses are less than the generated masses to some extent. These errors are caused by the uncertainties in different stages of the analysis process like jet reconstruction algorithm, \( b \) jet tagging procedure, fit functions, momentum and energy calculations of particles, etc. These uncertainties can be reduced by making further developments in jet cluster sequence, \( b \) jet tagging algorithm, measuring and fitting methods, etc. However, this study is not concerned with the implementation of such modifications. An average difference of all measured masses of \( m_{H_1} \) and \( m_{H_2} \) is determined from their generated values and it is found that these are 7.47 GeV and 8.59 GeV less from their generated values, respectively, and average mass error is 0.3521 and 0.4024 GeV, respectively. This average difference is added to the reconstructed masses of \( m_{H_1} \) and \( m_{H_2} \) to find the corrected reconstructed mass values. It can be observed that the corrected reconstructed masses of both heavy scalar Higgs bosons are well agreed with their generated masses.

4.3 Reconstruction of charged Higgs Bosons

The reconstruction of charged Higgs masses is possible from \( W \) and \( H \) bosons. Now those events are selected that have four \( b \) jets as well as four light jets simultaneously. Mass of positively charged Higgs boson expressed as \( m_{H^+} \) is determined from its supposed decay products i.e. \( W^+ \) boson and one heavy Higgs boson \( m_{H_1} \). Mass of negatively charged Higgs boson expressed as \( m_{H^-} \) is determined from its supposed decay products i.e. \( W^- \) boson and other heavy Higgs boson \( m_{H_2} \). As the mass distributions of both
The reconstructed mass of charged Higgs boson $H^+$ for all benchmark points.

![Reconstructed mass of charged Higgs boson $H^+$ for all benchmark points](image1)

The reconstructed mass of charged Higgs boson $H^-$ for all benchmark points.

![Reconstructed mass of charged Higgs boson $H^-$ for all benchmark points](image2)

Heavy Higgs bosons are almost similar to each other so the choice of heavy Higgs boson to reconstruct the charged Higgs boson will not affect the charged Higgs rebuilt masses significantly. Figure 12 shows the reproduced distributions for the mass of charged Higgs $m_{H^+}$ and Fig. 13 for the mass of charged Higgs $m_{H^-}$. The charged Higgs $m_{H^+}$ is represented as CH1 and charged Higgs $m_{H^-}$ is represented as CH2. It can be examined that the reconstructed masses using $\chi^2$ method is in agreement with the nominal mass for each BP. Figure 12 shows that the peak of the reconstructed mass of charged Higgs for BP1, BP2, BP3, and BP4 is at 248.15, 323.65, 398.65, and 404.55 GeV, respectively. Similarly Fig. 13 shows that the peak of reconstructed mass of charged Higgs for BP1, BP2, BP3, and BP4 is at 249.81, 324.81, 398.11, and 402.26 GeV, respectively. The reconstructed masses are obtained by fitting a suitable Gaussian function on the distribution curves of $H^+$ and $H^-$ and taking their mean values. The masses of charged Higgs $m_{H^+}$ and $m_{H^-}$ are less from their generated mass by an average of 10.65 GeV and 11.31 GeV, respectively, and the average mass error is 0.51 and 0.45 GeV, respectively. These values are added in the reconstructed masses of $m_{H^+}$ and $m_{H^-}$, respectively, to get corrected reconstructed masses. Tables 9 and 10 contain the data of generated, reconstructed, and corrected reconstructed masses of charged Higgs bosons. Gen. Mass is the mass of neutral heavy Higgs mass taken as BP which satisfies the constraints. Here it was generated.
Table 9 The generated mass, reconstructed mass, and corrected reconstructed mass of charged Higgs boson $H^+$ for all benchmark points

| Signal scenario | Gen. mass (GeV) | Recons. mass (GeV) | Corr.recons. mass (GeV) |
|-----------------|----------------|-------------------|------------------------|
| BP1             | 250            | 237.5 ± 0.4       | 248.15 ± 0.9           |
| BP2             | 325            | 313 ± 0.4         | 323.65 ± 0.9           |
| BP3             | 400            | 388 ± 0.6         | 398.65 ± 1             |
| BP4             | 400            | 393.9 ± 0.65      | 404.55 ± 1             |

Table 10 The generated mass, reconstructed mass, and corrected reconstructed mass of charged Higgs boson $H^-$ for all benchmark points

| Signal scenario | Gen. mass (GeV) | Recons. mass (GeV) | Corr.recons. mass (GeV) |
|-----------------|----------------|-------------------|------------------------|
| BP1             | 250            | 238.5 ± 0.29      | 249.81 ± 0.7           |
| BP2             | 325            | 313.5 ± 0.4       | 324.81 ± 0.8           |
| BP3             | 400            | 386.8 ± 0.42      | 398.11 ± 0.8           |
| BP4             | 400            | 390.95 ± 0.7      | 402.26 ± 1             |

4.4 Signal significance

To examine the visibility of charged Higgs boson at a linear collider, the significance of the signal is studied for charged Higgs mass distributions. Signal-to-background ratio, total efficiency, and signal significance are calculated for integrated luminosity 100, 500, 1000, and 5000 fb$^{-1}$, and the results are presented in Table 11. Although in this study the detector effects are not included however this process can be used as a discovery channel for charged Higgs boson at CLIC. Figure 14 shows the bin-wise filling of charged scalar Higgs mass values of all signal events and the total background events at 500 fb$^{-1}$. It can be seen that the signals are dominated by background events throughout the charged Higgs mass range. Table 11 shows the signal significance values at each benchmark point, at integrated luminosities of 100 fb$^{-1}$, 500 fb$^{-1}$, 1000 fb$^{-1}$, and 5000 fb$^{-1}$. Figure 15 shows the signal significance, against each benchmark point at integrated luminosities, 100 fb$^{-1}$, 500 fb$^{-1}$, 1000 fb$^{-1}$, and 5000 fb$^{-1}$. Figure 16 represents the signal significance deviations from standard model predictions in the considered bosonic decay channel as a function of twice the charged Higgs mass. The production of higher charged Higgs masses causes a reduction in the cross section which ultimately reduces the signal events at a specific value of integrated luminosity.

5 Conclusion

In this research work, 2HDM type I is considered as theoretical ground, and the scenario chosen in it is like SM in which lighter scalar Higgs $h$ behaves as standard model Higgs boson and $\sin(\beta - \alpha) = 1$. Four distinct points in the allowed region are considered and their credibility is checked by 2HDMC-1.7.0. The production and observability of charged Higgs pair $H^\pm$ through electron...
Table 11  Values of signal significance and efficiency for all benchmark points at integrated luminosities of 100 fb\(^{-1}\), 500 fb\(^{-1}\), 1000 fb\(^{-1}\), and 5000 fb\(^{-1}\)

|                  | BP1     | BP2     | BP3     | BP4     |
|------------------|---------|---------|---------|---------|
| Significance \(S/\sqrt{B}\) at100 fb\(^{-1}\) | 5.98    | 4.53    | 0.90    | 0.499   |
| Significance \(S/\sqrt{B}\) at 500 fb\(^{-1}\) | 13.39   | 10.14   | 2.01    | 1.11    |
| Significance \(S/\sqrt{B}\) at 1000 fb\(^{-1}\) | 18.94   | 14.35   | 2.85    | 1.57    |
| Significance \(S/\sqrt{B}\) at 5000 fb\(^{-1}\) | 42.35   | 32.09   | 6.38    | 3.52    |
| Total signal efficiency \(\epsilon_{\text{total}}\) | 0.00577 | 0.01302 | 0.00852 | 0.00833 |

Fig. 15  The signal significance corresponding to each benchmark point at integrated luminosities of 100 fb\(^{-1}\), 500 fb\(^{-1}\), 1000 fb\(^{-1}\), and 5000 fb\(^{-1}\)

Fig. 16  The signal significance versus twice of mass of charged Higgs expected at integrated luminosities of 100 fb\(^{-1}\), 500 fb\(^{-1}\), 1000 fb\(^{-1}\), and 5000 fb\(^{-1}\)
positional annihilation is investigated at four benchmark points in Compact Linear Collider. The series of decays in the signal process is given as $e^+e^→ Z^+/γ^+→ H^+H^−→ HW^±W^−→ jjbbjjb$ in which bosonic decay of charged Higgs is considered that involves $H^±W^±H$ vertex twice in a signal process. This coupling vertex is proportional to $\sin(\beta − \alpha)$ and momenta of charged Higgs and neutral scalar Higgs bosons. As the value of $\sin(\beta − \alpha)$ is set equal to unity so it is only proportional to the momentum of the particles involved. The value of $\tan\beta$ is kept relatively high to enhance the branching ratio $H → bb$ to benefit the signal processes.

In this work, a specific bosonic decay of charged Higgs boson is considered after its production which was not studied in detail till this time. The values of all Higgs masses are taken in such a way that they permit the assumed bosonic decay kinematically. The production cross section of the signal process is determined for each benchmark point at the different center of mass energies which has reasonable values which show that this process can be used to probe the charged Higgs boson experimentally. Ignoring the minor errors, all the measurements for reconstructed charged and neutral Higgs boson invariant masses are in good agreement with their generated masses. Analysis code is run for all the assumed scenarios separately and the signal selection efficiencies are calculated for all benchmark points. The results show that all the signals have sufficiently large total signal selection efficiencies. The reconstructed mass distributions of charged Higgs bosons and heavy Higgs bosons shows well high peaks. The analysis reveals that this process is favorable to discover the assumed scenarios for charged Higgs boson. Signal significance and total signal efficiency have been calculated for different integrated luminosities. The results prove that the charged Higgs is observable through pair production along with its bosonic decays. This study is supposed to provide the experimentalists with a good way to examine the Higgs bosons beyond SM as well as to check the validity of the 2HDM model in considered parameter space.

Data Availability Statements Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

References

1. S. Gasiorowicz, Elementary particle physics (1966)
2. P.W. Higgs, Broken symmetries, massless particles and gauge fields. Phys. Lett. 12, 132–133 (1964)
3. P.W. Higgs, Broken symmetries and the masses of gauge bosons. Phys. Rev. Lett. 13(16), 508 (1964)
4. F. Englert, B. Brout, Broken symmetry and the mass of gauge vector mesons. Phys. Rev. Lett. 13(9), 321 (1964)
5. G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles. Phys. Rev. Lett. 13(20), 585 (1964)
6. P.W. Higgs, Spontaneous symmetry breakdown without massless bosons. Phys. Rev. 145(4), 1156 (1966)
7. T.W.B. Kibble, Phys. Rev. 155, 1554 (1967)
8. J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, The Physics of the Higgs Bosons: Higgs Hunter’s Guide (1989)
9. B. Gustavo Castelo, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher, J.P. Silva, Theory and phenomenology of two-Higgs-doublet models. Phys. Rep. 516, 1–102 (2012)
10. M.S. Carena, D. Garcia, U. Nierste, C.E.M. Wagner, Nucl. Phys. B 577, 88 (2000). arXiv:hep-ph/9912516
11. S. Davidson, H.E. Haber, Phys. Rev. D 72, 099902 (2005). arXiv:hep-ph/0504050, Erratum: Phys. Rev. D72 099902 (2005)
12. G. Lee, C.E.M. Wagner, Phys. Rev. D 92, 075032 (2015). arXiv:1508.00576
13. E. Bagnaschi, F. Brümer, W. Buchmüller, A. Voigt, G. Weiglein, JHEP 03, 158 (2016). arXiv:1512.07761
14. E. Kneringer, Higgs searches at LEP2 with the ALEPH detector, in Electroweak Physics, Proceedings, eds. A. Astbury, B.A. Campbell, F.C. Khanna, J. Pinter, G.C. Viter (World Scientific, 2000), p. 414–421
15. ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, and LEP Higgs Working Group. Search for charged Higgs bosons: Preliminary combined results using LEP data collected at energies up to 209 GeV. arXiv:hep-ex/0107031 (2001)
16. A. Heister et al., ALEPH collaboration. Phys. Lett. B 543, 1 (2002)
17. J. Abdallah et al., DELPHI collaboration. Eur. Phys. J. C 34, 399 (2004)
18. P. Abreu et al., DELPHI collaboration. Phys. Lett. B 460, 484 (1999)
19. P. Acher et al., L3 Collaboration. Phys. Lett. B 575, 208 (2003)
20. G. Abbiendi et al., OPAL collaboration. Eur. Phys. J. C 72, 2076 (2012)
21. G. Abbiendi et al., OPAL collaboration. Eur. Phys. J. C 7, 407 (1999)
22. O. P. A. L. Collaborations, Search for charged Higgs bosons: combined results using LEP data. arXiv:1301.0605 (2013)
23. G. Abbiendi et al., ALEPH, DELPHI, L3, OPAL and LEP collaborations. Eur. Phys. J. C 73, 2463 (2013)
24. M. Aaboud, G. Aad, B. Abbott, O. Abdinov, B. Abeloos, D.K. Abhayasinghe, S.H. Abidi, et al., Search for charged Higgs bosons decaying via $H^± → τ ^±γ$, in Lepton and photon interactions at high energies, in Proceedings, 20th International Symposium, LP 2001, Rome, Italy, July 23–28, arxiv: hep-ex/0107031, http://webbibl.cern.ch/abstract/CERN-L3-NOTE-2689(2001)
25. T. Altmöller et al., (CDF), Phys. Rev. Lett. 103, 101803 arxiv: 0907.1269 (2009)
26. G. Aad et al., (ATLAS). JHEP 03, 088. arxiv:1412.6663 (2015)
27. G. Aad et al., (ATLAS). JHEP 03, 076. arxiv:1212.3572 (2013)
28. G. Aad et al., (ATLAS). Eur. Phys. J. C73, 2465. arxiv: 1302.3694 (2013)
29. G. Aad et al., (ATLAS). JHEP 06, 039. arxiv: 1204.2760 (2012)
30. CMS-PAS-HIG-11-008, CMS Collaboration (2011)
31. CMS-PAS-HIG-14-020, CMS Collaboration (2014)
35. A. Heister et al., ALEPH. Phys. Lett. B 543, 1 (2002). (hep-ex/0207054)
36. M. Aoki, R. Guedes, S. Kanemura, S. Moretti, R. Santos, K. Yagyu, Light charged Higgs bosons at the LHC in two-Higgs-doublet models. Phys. Rev. D 84(5), 055028 (2011)
37. A. Arhrib, R. Benbrik, S. Moretti, Bosonic decays of charged Higgs bosons in a 2HDM type-I. Eur. Phys. J. C 77, 621 (2017)
38. M. Aoki, S. Kanemura, K. Tsumura, K. Yagyu, Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology. Phys. Rev. D 80(1), 015017 (2009)
39. K. Cheung, et al., arXiv: 2201.06890
40. A.M. Sirunyan, T. Armen, A. Wolfgang, A. Federico, Thomas, B. Johannes, D. Marko et al., Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at $s = 13$ TeV. J. High Energy Phys. 2020(1), 1–48 (2020)
41. CLIC, The and Charles, TK and Giansiracusa, PJ and Lucas, TG and Rassool, RP and Volpi, M and Balazs, C and Afanacev, K and Makarenko, V and Patapenka, A and others, The Compact Linear Collider (CLIC)-2018 Summary Report. arxiv:1812.06018
42. M. Hashemi, H. Gholamhossein, Capability of future linear colliders to discover heavy neutral CP-even and CP-odd Higgs bosons within type-I 2HDM. J. Phys. G 45(2), 095005
43. M. Hashemi, G. Haghighat, Observability of 2HDM neutral Higgs bosons with different masses at future $e^+e^-$ linear colliders. Nucl. Phys. B 951, 114903 (2020)
44. P. Czodrowski, Search for Charged Higgs Bosons with the ATLAS Detector at the LHC, Ph.D. diss., Dresden, Tech. U. (2013)
45. M. Krawczyk, S. Moretti, P. Osland, G.M. Pruna, R. Santos, Prospects for 2HDM charged Higgs searches. J. Phys. Conf. Ser. 873(1), 012048 (2017)
46. M. Misiak, M. Steinhauser, Weak radiative decays of the B meson and bounds on $M_{H^\pm}$ in the Two-Higgs-Doublet Model. Eur. Phys. J. C 77(3), 1–9 (2017)
47. A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak, Status of the charged Higgs boson in two Higgs doublet models. Eur. Phys. J. C 3, 182 (2018)
48. A. Arhrib, B. Rachid, H. Hicham, M. Stefano, W. Yan, Y. Qi-Shu, Implications of light charged Higgs boson at the LHC Run III in the 2HDM. arXiv:2003.11108
49. S. Torbjörn, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2. Comput. Phys. Commun. 191, 159–177 (2015)
50. D. Eriksson, J. Rathmann, O. Stal, 2HDMC-two-Higgs-Doublet model calculator. Comput. Phys. Commun. 181, 189 (2010)
51. The reference manual can be obtained at the URL. http://lcgapp.cern.ch/project/simu/HepMC/
52. R. Brun, F. Rademakers, ROOT-an object oriented data analysis framework. Nucl. Instrum. Meth. A 389, 81–86 (1997)
53. A. Arhrib, R. Benbrik, S. Moretti, Bosonic decays of charged Higgs bosons in a 2HDM type-I. Eur. Phys. J. C 77(9), 1–6 (2017)
54. P. Czodrowski, Search for Charged Higgs Bosons with the ATLAS Detector at the LHC, Ph.D. diss., Dresden, Tech. U. (2013)
55. A.M. Sirunyan, T. Armen, A. Wolfgang, A. Federico, Thomas, B. Johannes, D. Marko et al., Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at $s = 13$ TeV. J. High Energy Phys. 2020(1), 1–48 (2020)
56. CLIC, The and Charles, TK and Giansiracusa, PJ and Lucas, TG and Rassool, RP and Volpi, M and Balazs, C and Afanacev, K and Makarenko, V and Patapenka, A and others, The Compact Linear Collider (CLIC)-2018 Summary Report. arxiv:1812.06018
57. M. Hashemi, H. Gholamhossein, Capability of future linear colliders to discover heavy neutral CP-even and CP-odd Higgs bosons within type-I 2HDM. J. Phys. G 45(2), 095005
58. M. Hashemi, G. Haghighat, Observability of 2HDM neutral Higgs bosons with different masses at future $e^+e^-$ linear colliders. Nucl. Phys. B 951, 114903 (2020)
59. P. Czodrowski, Search for Charged Higgs Bosons with the ATLAS Detector at the LHC, Ph.D. diss., Dresden, Tech. U. (2013)
60. R. Brun, F. Rademakers, ROOT-an object oriented data analysis framework. Nucl. Instrum. Meth. A 389, 81–86 (1997)
61. A. Arhrib, B. Rachid, H. Hicham, M. Stefano, W. Yan, Y. Qi-Shu, Implications of light charged Higgs boson at the LHC Run III in the 2HDM. arXiv:2003.11108
62. S. Torbjörn, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2. Comput. Phys. Commun. 191, 159–177 (2015)
63. D. Eriksson, J. Rathmann, O. Stal, 2HDMC-two-Higgs-Doublet model calculator. Comput. Phys. Commun. 181, 189 (2010)
64. The reference manual can be obtained at the URL. http://lcgapp.cern.ch/project/simu/HepMC/
65. R. Brun, F. Rademakers, ROOT-an object oriented data analysis framework. Nucl. Instrum. Meth. A 389, 81–86 (1997)
66. A. Arhrib, B. Rachid, H. Hicham, M. Stefano, W. Yan, Y. Qi-Shu, Implications of light charged Higgs boson at the LHC Run III in the 2HDM. arXiv:2003.11108
67. S. Torbjörn, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2. Comput. Phys. Commun. 191, 159–177 (2015)
68. A. Djouadi, J. Kalinowski, P.M. Zerwas, Two-and three-body decay modes of susy Higgs particles. Zeitschrift für Physik C Particles and Fields 70(3), 435–447 (1996)
69. S. Moretti, W.J. Stirling, Phys. Lett. B 347, 291 Erratum: [Phys.Lett.B366, 451 (1996)] [hep-ph/9412209, hep-ph/9412209 (1995)]
70. A.G. Akeroyd, Three-body decays of Higgs bosons at LEP2 and application to a hidden fermiophobic Higgs. Nucl. Phys. B 544(3), 557–575 (1999)
71. A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti, S. Munir, Identifying a light charged Higgs boson at the LHC Run II. Phys. Lett. B 774, 591–598 (2017)
72. H. Henning, T. Stefaniak, J. Wittbrodt, The forgotten channels: charged Higgs boson decays to a $W^{pm}$ and a non-SM-like Higgs boson. J. High Energy Phys. 2021(6), 183 (2021)
73. D. Eriksson, J. Rathmann, O. Stal, 2HDMC-two-Higgs-doublet model calculator. arXiv:0902.0851
74. E. Boos et al., CompHEP 4.4–automatic computations from lagrangians to events. Nucl. Instrum. Meth. A 534, 250–259 (2004)
75. A. Buch, et al., CompHEP-a package for evaluation of n diagrams and integration over multi-particle phase space. arXiv: hep-ph/9908288 (1999)
76. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. Eur. Phys. J. C 3, 1896 (2012)
77. M. Cacciari, G.P. Salam, G. Soyez, The anti-kt jet clustering algorithm. JHEP 4063 (2008)