Observability of 2HDM neutral Higgs bosons in fully hadronic decay at future linear collider

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Abstract The study aims to investigate the observability of pseudoscalar Higgs boson A and neutral heavy CP even Higgs boson H, at different benchmark points, in the framework of type-I 2HDM. The study is done for $e^- e^+$ collisions at $\sqrt{s} = 1000$ GeV center of mass energy (c.m.s.), a possible scenario in future lepton collider. The associated production of A and H in $e^+ e^-$ collisions are investigated in a fully hadronic final state in two different channels. The first one is $A H \rightarrow Z H H \rightarrow j \bar{j} b \bar{b} b \bar{b}$, while the other one is $A H \rightarrow b \bar{b} b \bar{b}$. The observability of neutral heavy Higgs and pseudoscalar Higgs signal is possible within the parameter space $(\tan \beta, m_A)$ which satisfies all experimental and theoretical constraints. The CP odd and CP even Higgs bosons in all scenarios are observable when the signal exceeds $5\sigma$, which is the final extracted value of signal significance. The signal significance is calculated at different integrated luminosities. It is concluded from the current analysis that a fully hadronic channel is promising for search and measurement of the neutral Higgs bosons in 2HDM.

1 Introduction

After decades of continuous searches, the Standard Model (SM) Higgs boson was discovered by the CMS and ATLAS experiments at the Large Hadron Collider (LHC) in 2012. This proved to be the cornerstone in a very successful theory that passed all of the experimental tests. Yet there are several reasons which lead us to believe that this is at best an incomplete theory. This opens a way for physics that is beyond the standard model BSM. The BSM comprises many theories, but to establish any of these, experimental evidence is required. The Two Higgs Doublet Model 2HDM is a model that provides a simple extension to the standard model and features many BSM theories including the Minimal Supersymmetric Standard Model MSSM. There are eight degrees of freedom in two doublet model out of which three degrees of freedom are eaten up by the electroweak bosons due to electro-weak symmetry breaking. The remaining five degrees of freedom lead to five physical Higgs bosons that are 2 CP-even neutral scalar Higgs bosons $h$, $H$, a CP-odd pseudoscalar neutral Higgs boson $A$ and a pair of charged Higgs bosons $H^\pm$. The existence of these Higgs bosons is to be verified through experimental measurements of production cross sections and branching ratios. In July 2017, ATLAS published the results for collaboration on the trending search of decaying neutral Higgs collaboration into two tau leptons. The tau leptons are individually interesting to search due to the existence of large coupling of A/H and fermions of down type for the specific value of MSSM provided parameter space. These will certainly boost up the probability of A/H production following b-quarks and provides a higher cross section. Future lepton colliders such as $e^- e^+$ will play an important role in the detection of the Higgs boson. The precise attention is given to search the Higgs boson. The main focus of this study is to investigate the production of neutral Higgs A in association with H at electron-positron collider. The assumed framework for the study is Type 1 2HDM. Several benchmark points are assumed with different mass hypotheses. Two decay channels are investigated in this study. In the first one, the pseudoscalar Higgs A decays to Z boson along with neutral CP even heavy Higgs boson $H$, the Z boson then decays hadronically to quarks, while the H boson decays to $b \bar{b}$ leading to two light-jets and four b-jets in the final state ($j b b \bar{b} b$). The Feynman diagram for the first process is given in Fig. 1.

In the second decay channel, both A and H decay to b-quarks leading to four b-jets in the final state ($b b \bar{b} b$). The Feynman diagram of this process is given in Fig. 2.
The 2HDM is an extension of the SM which is featured in many BSM theories. This model is proficient in solving some of the problems in SM while still maintaining the good agreement between the SM and experiments. The 2HDM offers the most simple extension of the SM where the Higgs sector is extended by including an additional doublet in the theory. The supersymmetric theories show that the scalars are associated with chiral multiplets and opposite chirality is found in their complex conjugates. The most attractive feature of 2HDM is that it smoothens the way for initiating new possibilities for explicit or for automatic CP violation [1]. Each class of 2HDM gives an interesting environment and unique phenomenology. The 2HDM is divided into four types depending on the coupling of fermions with the doublets as shown in Table 1.

The general scalar of 2HDM is the most usual scalar potential of 14 parameters which can function as charge parity (CP) conserving, parity-violating and charge violating minima. The common scalar potential expression is assumed for two doublets $\phi_1$ and $\phi_2$ [2] with hypercharge $+1$ and is given in Eq. (1)

$$V_{2HDM} = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 (\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2)$$

$$+ \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_5 [(\phi_1^\dagger \phi_1) + (\phi_2^\dagger \phi_2)]$$

(1)

This potential contains all real parameters with two assumed $SU(2)$ doublets in 2HDM. $v_1$ and $v_2$ are the values of vacuum expectation of two doublets, i.e., $\phi_1$ and $\phi_2$. The doublet expanded by making known to eight read field $w_i^\pm, \rho_i, \eta_i (i = 1, 2 \ldots )$ all over the place of these minima is given in Eq. (2)
\[ \langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \] (2)

\[ \langle \phi_1 \rangle = \left( \frac{u_1^+}{\sqrt{2}} \right) \begin{pmatrix} v_1 + \rho_1 + i n_1 \\ \sqrt{2} \end{pmatrix}, \langle \phi_2 \rangle = \left( \frac{u_2^+}{\sqrt{2}} \right) \begin{pmatrix} v_2 + \rho_2 + i n_2 \\ \sqrt{2} \end{pmatrix} \] (3)

By implementing the two minimization conditions of 2HDM, the terms \( m_{11}^2 \) and \( m_{22}^2 \) can be eliminated in the favor of pseudoscalar inputs. By the use of conditions, seven real independent parameters \( \tan \beta = \frac{v_2}{v_1}, m_{11}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \) are obtained.

To be more convenient, the other parameters would be \( m_b, m_H, m_A, m_{H^\pm}, \alpha, \tan \beta, m_{12}^2 \), where \( \alpha \) is the mixing angle which rotates non-physical states (\( \phi_1 \) and \( \phi_2 \)) to the physical states (\( h \) and \( H \)). For Yukawa Lagrangian, the procedure as in SM cannot be followed and if both of the Higgs doublets couples to SM fermions, this would be flavor violating. To overcome this problem, the discrete symmetry \( Z_2 \) is imposed.

A discrete \( Z_2 \) symmetry [3] was forced on the 2HDM potential to avoid FCNCs [4] but the potential still contains a term that breaks this symmetry. If \( m_{12}^2 \) is not disappearing, the potential is not invariant under the transformation \( \phi_1 \rightarrow \phi_2 \) but this form of symmetry breaking is only soft because \( m \) has mass dimension. The constraints are applied to 2HDM parameters by some of the theoretical considerations like perturbativity, vacuum stability, and perturbative unitarity. Consistency is checked at the confidence level of 95%.

### 3 Signal process

The observability of neutral Higgs bosons is investigated in two final states. In the first one, we have signal chain process \( e^- e^+ \rightarrow AH \rightarrow ZHH \rightarrow j j b b b b \), and in the second final state, the chain process is \( e^- e^+ \rightarrow AH \rightarrow b b b b \) within the framework of type 1 2HDM in the low \( \tan \beta \) regime, and enhancement of \( A \) and \( H \) is achieved. The \( Z \) boson goes into hadronic decay as a di-jet pairs \( j j \), \( Z \rightarrow j j \). The enhancement of the Higgs boson decay mode \( H \rightarrow b b \) is due to the \( \cot \beta \) factor. The several benchmark points with a different mass hypotheses are assumed in the parameter space of the 2HDM and are shown in Table 2. At linear collider, the initial collision is assumed to take place at the center of mass energy \( \sqrt{s} = 1000 \text{ GeV} \), and integrated luminosity is assumed to be 500 \( fb^{-1} \). The range for the mass of the CP-even Higgs boson \( H \) is assumed to be from 150 to 300 GeV, and for CP-odd Higgs boson \( A \), the assumed range is 250–400 GeV with the mass splitting of 50–100 in all the scenarios. The value of \( \tan \beta \) is set to 10 for all scenarios which result in the enhancement of \( H \) decay. To satisfy the theoretical requirement of potential stability [5], there is a range of \( m_{12}^2 \) parameter for each scenario. By using 2HDMC-1.7.0 [6], perturbativity and unitarity constraints are checked.

In LEP [7], the experimental constraint limits the deviation of \( \rho = m_W^2 (m_Z \cos \theta_W)^{-2} \) from its SM value. To obey this constraint, the values of masses of Higgs bosons \( H^\pm \) and \( m_A \) are assumed to be the same for all benchmark points. Another condition to satisfy this constraint [8,9] is either \( m_A = m_{H^\pm} \) or \( m_H = m_{H^\pm} \). The LHC experiment [10] has excluded the mass regions \( m_H = 150, 200, 250 \text{ GeV} \) for \( m_A = 310–410, 335–400, 350–400 \text{ GeV} \), respectively, in the Type-I 2HDM at \( \tan \beta = 10 \). Another limit in LHC experiments [11,12] on pseudoscalar Higgs is \( m_A > 350 \text{ GeV} \) for \( \tan \beta < 5 \) in the Type-I. The mass range \( m_H = 170–360 \text{ GeV} \) has been excluded in another LHC experiment [13] for \( \tan \beta < 1.5 \) in Type-I. The assumed benchmark points in Table 2 satisfy the constraints resulting from LHC observations. The constraints on the charged Higgs from flavor physics data are \( m_{H^\pm} > 700 \text{ GeV} \) (\( \tan \beta < 2 \)) and \( m_{H^\pm} > 570 \text{ GeV} \) (\( \tan \beta > 2 \)) in Type-II 2HDM [14,15]. For \( \tan \beta > 2 \), no condition limits the Type-I. From the review of Tevatron, LEP and LHC results, it is shown that in Type-I, there is no exclusion around \( m_{H/A}/H^\pm = 500 \text{ GeV} \) for \( \sin(\beta - \alpha) = 1 \) [16]. In the MSSM, the constraints on the masses of charged Higgs bosons and pseudoscalar Higgs bosons are \( m_{H^\pm} \geq 78.6 \text{ GeV} \) and \( m_H \geq 93.4 \text{ GeV} \) [17,18]. In this model, the mass range \( m_{A/H} = 200 - 400 \text{ GeV} \) has been excluded for \( \tan \beta \geq 5 \), in LHC experiments [19,20]. The parameter spaces, Higgs fermion coupling constants, structures, etc., of Type-I and MSSM are different so there is no effect of constraints of MSSM on Type-I 2HDM. From BABAR collaboration, the measured values of ratios of \( R(D) \) and \( R(D^\ast) \) are 0.440 ± 0.058 ± 0.042 and 0.332 ± 0.024 ± 0.018. These values match the predictions of particular Higgs model for \( \tan \beta/m_{H^\pm} = 0.440 \pm 0.02 \text{ GeV}^{-1} \) and \( \tan \beta/m_{H^\pm} = 0.75 \pm 0.04 \text{ GeV}^{-1} \), respectively. \( R(D) \) and \( R(D^\ast) \) excludes the 2HDM charged Higgs boson at 99.8% confidence level. The range for \( m_{H^\pm} > 15 \text{ GeV} \) [21,22]. The value of \( m_{H^\pm} \leq 15 \text{ GeV} \) has been excluded by \( B \rightarrow X_{sY} \) measurements [23]. The assumed benchmark points in this study are consistent with the theoretical and experimental constraints and are safe to use.

Branching ratios (BR) are achieved by using 2HDMC-1.7.0 [6]. B-tagging and jet reconstruction algorithms give rise to uncertainties which perturb the final results due to more errors in the hadronic \( Z \) boson decay. The \( Z \) boson decay provides a simple and clean signature at the linear collider. The branching ratio of hadronic decay of \( Z \) boson is \( BR(Z \rightarrow q\bar{q}) \approx 0.69 \) and the BR for \( H \) decay is \( BR(H \rightarrow b\bar{b}) \approx 0.71 \). In the \( AH \rightarrow ZHH \) process, the \( Z \) and \( H \) Higgs boson are reconstructed by recombination of two light-jets and two b-jets respectively. The pseudoscalar \( A \) Higgs boson is then reconstructed by the reconstructed \( Z \) and \( H \) bosons.

In the second process, both \( A \) and \( H \) are reconstructed by recombination of b-jet pairs.
and are given in Table 2. The cross section for the first process is represented by

\[
\sigma_{1}(fb) \text{ at } \sqrt{s} = 1000 \text{ GeV}
\]

The parameters of Type-1 are produced in SLHA (SUSY Les Houches Accord) format by using 2HDMC-1.7.0 [6]. This output file is passed to PYTHIA 8.2.10 [24] to generate the events. The generated particles in each event are then passed to clustering algorithm fastjet-3.3.3 to make jets [25]. To record the events data, the interface of HepMC-2.06.06 [26] is given to Pythia. The output of Pythia is then analyzed, and histograms are plotted by using Root-6.20/04 [27].

### Table 2: Cross section for signals at different benchmark points and for SM background processes

| $m_{h}$ | $m_{H}$ | $m_{A}$ | $m_{H^\pm}$ | $m_{H_{12}}$ | $\tan\beta$ | $\sin(\beta - \alpha)$ | $\sigma_{1}(fb)$ at $\sqrt{s} = 1000$ GeV | $\sigma_{1}(fb)$ at $\sqrt{s} = 1500$ GeV | $\sigma_{1}(fb)$ at $\sqrt{s} = 3000$ GeV |
|--------|--------|--------|-------------|-------------|--------------|-----------------|-------------------------------|-------------------------------|-------------------------------|
| 125    | 150    | 250    | 250         | 1987–2243   | 10           | 1               | 10.16                        | 5.587                         | 1.692                         |
| 125    | 200    | 300    | 300         | 3720–3975   | 10           | 1               | 8.211                        | 5.137                         | 1.628                         |
| 125    | 250    | 330    | 330         | 5948–6203   | 10           | 1               | 6.675                        | 4.725                         | 1.484                         |
| 125    | 300    | 400    | 400         | 8671–8925   | 10           | 1               | 4.213                        | 3.937                         | 1.294                         |

### Table 3: Branching ratio of neutral Higgs boson $H$ decay for benchmark points

| BP    | $BR(H \rightarrow b\bar{b})$ | $BR(H \rightarrow \tau\tau)$ | $BR(H \rightarrow gg)$ |
|-------|-------------------------------|-------------------------------|-------------------------|
| 200   | $6.755 \times 10^{-1}$        | $7.133 \times 10^{-2}$        | $2.22 \times 10^{-1}$   |
| 225   | $4.474 \times 10^{-1}$        | $4.831 \times 10^{-2}$        | $1.957 \times 10^{-1}$  |
| 250   | $4.668 \times 10^{-2}$        | $5.139 \times 10^{-3}$        | $2.681 \times 10^{-2}$  |
| 275   | $4.568 \times 10^{-3}$        | $5.118 \times 10^{-4}$        | $3.429 \times 10^{-3}$  |
| 300   | $7.625 \times 10^{-5}$        | $8.679 \times 10^{-6}$        | $7.525 \times 10^{-5}$  |
| 325   | $1.839 \times 10^{-5}$        | $2.124 \times 10^{-6}$        | $2.446 \times 10^{-5}$  |

### Table 4: Branching ratio of pseudoscalar $A$ decay for benchmark points

| BP    | $BR(A \rightarrow ZH)$ | $BR(A \rightarrow Z\gamma)$ | $BR(A \rightarrow gg)$ | $BR(A \rightarrow Z\mu)$ |
|-------|------------------------|-----------------------------|------------------------|--------------------------|
| 200   | $6.279 \times 10^{-1}$ | $5.590 \times 10^{-5}$      | $1.6666 \times 10^{-1}$ | $6.777 \times 10^{-5}$   |
| 225   | $0.9098 \times 10^{-1}$ | $1.582 \times 10^{-5}$      | $3.389 \times 10^{-2}$  | $1.188 \times 10^{-5}$   |
| 250   | $0.9896 \times 10^{-1}$ | $4.279 \times 10^{-7}$      | $8.944 \times 10^{-4}$  | $2.101 \times 10^{-7}$   |
| 275   | $0.9863 \times 10^{-1}$ | $8.6 \times 10^{-8}$        | $1.603 \times 10^{-4}$  | $2.814 \times 10^{-8}$   |
| 300   | $0.7406 \times 10^{-1}$ | $4.308 \times 10^{-8}$      | $7.327 \times 10^{-5}$  | $9.259 \times 10^{-9}$   |
| 325   | $0.5605 \times 10^{-1}$ | $3.303 \times 10^{-8}$      | $5.120 \times 10^{-5}$  | $3.792 \times 10^{-9}$   |

The main SM background processes which are taken into account for this analysis, relevant to signal are pair production of di-vector boson $W^{\pm}$, $ZZ$, top quark $t\bar{t}$ and $Z/\gamma$ production. Cross sections are computed at $\sqrt{s} = 1000$ GeV by PYTHIA 8.2.10 [24] and are given in Table 2. The cross section for the first process is represented by $\sigma_{1}$, and for the second process, it is represented by $\sigma_{2}$.

The branching ratio for the decay of neutral Higgs boson $H$ into bottom quark pairs for our assumed BP points is calculated by using 2HDMC-1.7.0. Branching ratios of heavy neutral Higgs bosons $H$ and pseudoscalar $A$ Higgs boson decay for different benchmark points are tabulated in Tables 3 and 4 respectively.

### 4 Event generation, signal selection, and analysis

The parameters of Type-1 are produced in SLHA (SUSY Les Houches Accord) format by using 2HDMC-1.7.0 [6]. This output file is passed to PYTHIA 8.2.10 [24] to generate the events. The generated particles in each event are then passed to clustering algorithm fastjet-3.3.3 to make jets [25]. To record the events data, the interface of HepMC-2.06.06 [26] is given to Pythia. The output of Pythia is then analyzed, and histograms are plotted by using Root-6.20/04 [27].

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Table 5  Efficiencies for different selection cuts at different mass hypothesis in the first process

| Cuts              | BP 1   | BP 2   | BP 3   | BP 4   |
|-------------------|--------|--------|--------|--------|
| Two light-jets    | 0.4078 | 0.5122 | 0.5072 | 0.6249 |
| Four b-jets       | 0.5945 | 0.6364 | 0.6270 | 0.6496 |
| $\chi^2$          | 0.6356 | 0.5271 | 0.2910 | 0.3408 |
| Total Efficiency  | 0.1541 | 0.1718 | 0.0925 | 0.1384 |
| $\sigma \times BR[fb]$ | 4.481  | 2.886  | 1.715  | 0.580  |

Table 6  Efficiencies for different selection cuts at different mass hypothesis in the second process

| Cuts              | BP 1   | BP 2   | BP 3   | BP 4   |
|-------------------|--------|--------|--------|--------|
| Four b-jets       | 0.7161 | 0.7221 | 0.7167 | 0.7059 |
| $\chi^2$          | 0.7764 | 0.6766 | 0.6036 | 0.5053 |
| $A\chi^2$         | 0.8118 | 0.8013 | 0.8024 | 0.8207 |
| Total Efficiency  | 0.4514 | 0.3915 | 0.3471 | 0.29   |
| $\sigma \times BR[fb]$ | 4.0904×10^{-3} | 2.9431×10^{-2} | 6.7996×10^{-2} | 4.74×10^{-4} |

Different kinematic selection cuts are applied which arises certain fluctuations in the signal. 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.

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

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 a $\Delta R$ matching of the jets with the generated particles which are 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 $jjb\bar{b}b\bar{b}$ channel, we require the event to have at least two light-jets and at least four b-jets, while for $b\bar{b}b\bar{b}$, we require at least four b-tagged jets.

In $AH \rightarrow ZHH \rightarrow jjb\bar{b}b\bar{b}$ analysis, we use the selected light-jets (b-jets) to find a combination that minimize the $\chi^2$ defined as follows.

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

where $m_{jj,bb}$ are the dijet mass, $m_Z$ is the mass of $Z$ boson, and $m_H$ is the mass of the heavy Higgs boson according to the BP taken, and the $\sigma_{m_Z,H}$ are the widths of the respective mass distributions. The cut of $\chi^2 < 10$ is applied to select only events with good reconstructed $Z$ and $H$ bosons. The pseudoscalar Higgs boson $A$ is then reconstructed using the combination of $Z$ and $H$ which gives mass nearest to $A$ nominal mass according to the BP. The same treatment is given to $AH \rightarrow b\bar{b}b\bar{b}$ analysis but in this case, $\chi^2$ is defined as

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

After applying different selections cuts, the efficiencies are calculated for different benchmark points and are given in Table 5 for the first process and Table 6 for the second process, respectively.

5 Result and discussion

In the finalized results, the topology of our assumed first signal process contains four b-jets and two light-jets. The distribution of b-jet multiplicity for the process having four b-jets and two light-jets is shown in Fig. 3. More than 60 percent of the jets are passed
Fig. 3 Distributions of b-jet multiplicity corresponding to different background and signal processes at CMS energy of 1000 GeV

The distribution of light-jet multiplicity for this process is shown in Fig. 4 for both background and signal events. The other process contains 4 b-jets. The distribution of b-jet multiplicity for this process is shown in Fig. 5.

The distribution of b-jets slightly depends on neutral Higgs boson mass in the assumed signal event. The production of b-jet is suppressed kinematically in the production of Higgs boson, the availability of phase space is smaller due to which it decays to bottom quarks. Transverse energy $E_T$ of jets for the second process is shown in Fig. 6. The pseudorapidity of jets for this process is shown in Fig. 7.

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. 8, the b-jets can easily be identified by finding the minima of the plot. For all the distribution profiles, the implemented integrated luminosity is $500 \, fb^{-1}$. The cross sections of the signal are collected by multiplying the branching ratios with corresponding total cross sections and are given in Table 5 for the first process and in Table 6 for the second process.

5.1 Mass reconstruction

The invariant mass of neutral scalar Higgs bosons is reconstructed. In this work, the generation of signal and background processes is 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 would be produced by the proper mass variable.
**Fig. 5** Distributions of b-jet multiplicity for corresponding to different background and signal processes at CMS energy of 1000 GeV

**Fig. 6** Transverse energy of jets

**Fig. 7** Pseudorapidity of jets
By this process, the large signal will be produced over the background ratio. The pair of b-jets 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

$$m_H = \sqrt{E^2 - p_x^2 - p_y^2 - p_z^2}$$

(8)

6 Chi-square method

Chi-square test is based on comparing observed and expected values. This test is designed to determine whether a difference between actual and predicted data is due to chance or due to the relationship between the variables under consideration. As a result, Chi-square test is a fantastic tool for analyzing and understanding the relationships between our categorical data. The Chi-square method is used in this study to compare the reconstructed and actual values of Higgs boson mass. To determine the best estimate of Higgs-boson mass, I minimized the appropriately weighted sum of squared differences between observed and predicted values, known as “Chi-square.” The general formula for Higgs boson is given in Eq. (9)

$$\chi^2 = \left(\frac{m_{\text{rec}} - m_{\text{Gen}}}{\sigma_{\text{dijet}}}\right)^2.$$ 

(9)

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 “$m_{\text{Gen}}$.” 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.

$$\chi^2_{\text{min}} > 20$$

Then, using this true light-jet pair, the Higgs boson mass is reconstructed. The reconstructed invariant mass of Higgs boson from b-jet pairs and light-jet pairs for all signals along with SM backgrounds are shown in figures. Figures 9 and 10 represent the reconstruction of the neutral scalar Higgs for the first process.

The reconstruction of neutral Higgs boson is plotted in Fig. 11 for the second process.

The mass peak of neutral scalar Higgs is shown in Fig. 11 which suppresses the significant background processes. From Figs. 9, 10 to 11, it can be examined that the attained data fall nearly to the input mass which is only possible due to the testing of the different mass hypothesis of neutral scalar Higgs in simulation.

6.1 Mass reconstruction of pseudoscalar Higgs

In our assumed signal process, the decay of the A Higgs boson occurs as $A \rightarrow ZH$. In accordance with that scenario, the jets which successfully pass the cuts, A candidate are considered by identifying the combination of b-jets. In events with possible two candidates of H, the smallest value of the parameter $\Delta R$ of the combination of ZH is clearly assumed as A candidate. The plot for the reconstruction of pseudoscalar Higgs A for the first and second process is shown in Figs. 12 and 13, respectively.
6.2 Mass reconstruction of Z boson

The jets are assumed as light-jets which do not fulfill the requirements for the declaration of b-jets. For obtaining the reconstructed invariant mass of the Z boson, two of the leading jets are mainly selected which have the same $\eta$ and $p_T$ cuts implemented on all jets. The feature, low jet multiplicity of the signal events, is used for the suppression of the Z single events. The two light-jets having the highest $p_T$ are fused together to create the candidate of Z-boson.

The functions which are properly fit are mainly fitted to the distributions of signal and the finalized results are indicated with the error bars. The significant peaks in the fitted profiles are near to the Higgs masses which are generated in our scenario. ROOT 6.20 [27] is used for the fitting process. The Gaussian function was observed in the signal distributions of fit functions. The signal was covered by the Gaussian function. To find out the central region of a signal peak, the parameter “Mean” is used which is the parameter of the fit function of Gaussian. Values of the parameter Mean are assumed as reconstructed masses of Higgs bosons which are termed as $m_{\text{Rec}}$. For the comparison, it also indicates the generated masses which are termed as $m_{\text{Gen}}$. There is a difference between the reconstructed and generated masses due to arising uncertainties, from the algorithm of jet clustering and the misidentification of jets, rate of mistagging jet, method of fitting and the selection of the fit function, errors arising in the energy and the momentum of particles, etc. The error factor may be reduced by the process of optimization of the algorithm of jet clustering, the algorithm...
Fig. 11 Reconstructed mass of neutral Higgs at different mass hypothesis for the second process

![Mass reconstruction of neutral Higgs](image1)

Fig. 12 Mass reconstruction of pseudoscalar Higgs A for the first process

![Mass reconstruction of pseudoscalar Higgs A](image2)

Fig. 13 Mass reconstruction of pseudoscalar Higgs A for the second process

![Mass reconstruction of pseudoscalar Higgs A](image3)
Table 7  Generated, reconstructed, and corrected reconstructed mass of neutral scalar Higgs H1 in the first process

| BP   | mGen | mRec   | mCor.Rec. |
|------|------|--------|-----------|
| BP1  | 150  | 140.3 ± 0.1 | 152.86 ± 0.2 |
| BP2  | 200  | 186.4 ± 0.1  | 198.96 ± 0.2  |
| BP3  | 250  | 236.5 ± 0.1  | 249.06 ± 0.2  |
| BP4  | 300  | 286.5 ± 0.1  | 299.06 ± 0.2  |

Table 8  Generated, reconstructed, and corrected reconstructed mass of pseudoscalar Higgs A in the first process

| BP   | mGen | mRec   | mCor.Rec. |
|------|------|--------|-----------|
| BP1  | 250  | 229.96 ± 0.16 | 243.84 ± 0.43 |
| BP2  | 300  | 277.2 ± 0.12 | 291.08 ± 0.39 |
| BP3  | 330  | 337.8 ± 0.61 | 323.92 ± 0.88 |
| BP4  | 400  | 379.89 ± 0.12 | 393.77 ± 0.45 |

Table 9  Generated, reconstructed, and corrected reconstructed mass of neutral scalar Higgs H in the second process

| BP   | mGen | mRec   | mCor.Rec. |
|------|------|--------|-----------|
| BP1  | 150  | 139.9 ± 0.1 | 153.8 ± 0.13 |
| BP2  | 200  | 186.5 ± 0.009 | 200.4 ± 0.039 |
| BP3  | 250  | 234.4 ± 0.007 | 248.3 ± 0.037 |
| BP4  | 300  | 283.6 ± 0.007 | 297.5 ± 0.037 |

Table 10  Generated, reconstructed, and corrected reconstructed mass of pseudoscalar Higgs A in the second process

| BP   | mGen | mRec   | mCor.Rec. |
|------|------|--------|-----------|
| BP1  | 250  | 233.9 ± 0.1027 | 250.95 ± 0.1327 |
| BP2  | 300  | 282.5 ± 0.008 | 299.95 ± 0.038 |
| BP3  | 330  | 312.383 ± 0.007 | 329.433 ± 0.037 |
| BP4  | 400  | 383 ± 0.007 | 400.05 ± 0.037 |

of b-tagging and the method of fitting. Generated, reconstructed, and corrected reconstructed mass of neutral scalar Higgs H1 and pseudoscalar Higgs A is shown in Tables 7 and 8. From Tables 7 and 8, the average difference between the generated mass and reconstructed mass of H1 and A is 12.56 and 13.88, respectively, for the first process, and average mass error is 0.1 and 0.27, respectively. This error is reduced by adding the same value in the reconstructed mass and given in mCor.Rec. Similarly, average value of error is added in all error values and given in the third column. From Tables 7 and 8, it is concluded that reconstructed mass is a few GeV different from generated mass.

7 Signal significance

To figure out the observability in our assumed scenario of A and H Higgs bosons, for each one of the distributions of the candidate mass, the significance of the signal is computed. The numbers of candidate masses in signal and background events are counted in the whole mass series. Mainly the jets are not easily detected as the b-jets due to the production of several jets in the ongoing events. In the assumed scenario, several techniques are used to identify the jets. The associated jets are identified through the process of tagging which is aptly known as the algorithm of b-tagging. To identify the b-jets, the minimum distance between the b-parton and all of the generated jets is calculated. The term delta R is helpful in finding out the b-jets by calculating the distance between the
Table 11 Values of signal significance for all benchmark points at 100, 500, 1000 and 5000 \(fb^{-1}\) for neutral Higgs \(H_{1}\) in the first process

| BP1       | BP2       | BP3       | BP4       |
|-----------|-----------|-----------|-----------|
| Significance \(S/\sqrt{\mathcal{B}}\) at 100 \(fb^{-1}\) | 25.7142   | 18.1606   | 2.14265   | 2.74433   |
| Significance \(S/\sqrt{\mathcal{B}}\) at 500 \(fb^{-1}\) | 57.49     | 40.60     | 6.22      | 6.13      |
| Significance \(S/\sqrt{\mathcal{B}}\) at 1000 \(fb^{-1}\) | 81.31     | 57.42     | 8.80      | 8.6       |
| Significance \(S/\sqrt{\mathcal{B}}\) at 5000 \(fb^{-1}\) | 181.82    | 128.415   | 19.69     | 19.40     |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 100\) | 0.1541    | 0.168993  | 0.0785    | 0.11      |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 500,1000,5000\) | 0.1541    | 0.168993  | 0.080     | 0.11      |

Table 12 Values of signal significance for all benchmark points at 100, 500, 1000 and 5000 \(fb^{-1}\) for pseudoscalar Higgs \(A\) in the first process

| BP1       | BP2       | BP3       | BP4       |
|-----------|-----------|-----------|-----------|
| Significance \(S/\sqrt{\mathcal{B}}\) at 100 \(fb^{-1}\) | 106.535   | 67.76     | 4.71      | 1.21      |
| Significance \(S/\sqrt{\mathcal{B}}\) at 500 \(fb^{-1}\) | 238.219   | 151.525   | 10.553    | 3.114     |
| Significance \(S/\sqrt{\mathcal{B}}\) at 1000 \(fb^{-1}\) | 337.163   | 214.288   | 14.92     | 4.03      |
| Significance \(S/\sqrt{\mathcal{B}}\) at 5000 \(fb^{-1}\) | 753.316   | 479.163   | 33.3724   | 10.1189   |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 100,1000\) | 0.14      | 0.14      | 0.0569755 | 0.093     |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 500,5000\) | 0.1484    | 0.1484    | 0.0569755 | 0.13      |

Table 13 Values of signal significance for all benchmark points at 100, 500, 1000 and 5000 \(fb^{-1}\) for pseudoscalar Higgs \(A\) in the second process

| BP1       | BP2       | BP3       | BP4       |
|-----------|-----------|-----------|-----------|
| Significance \(S/\sqrt{\mathcal{B}}\) at 100 \(fb^{-1}\) | 0.00135   | 2.55      | 12.914    | 0.078     |
| Significance \(S/\sqrt{\mathcal{B}}\) at 500 \(fb^{-1}\) | 0.0030    | 5.70      | 28.876    | 0.175     |
| Significance \(S/\sqrt{\mathcal{B}}\) at 1000 \(fb^{-1}\) | 0.004269  | 8.066     | 40.8375   | 0.2478    |
| Significance \(S/\sqrt{\mathcal{B}}\) at 5000 \(fb^{-1}\) | 1.138     | 18.036    | 91.3155   | 0.5543    |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 100,500,1000\) | 0.000584515 | 0.153476  | 0.336317  | 0.2927    |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 5000\) | 0.30916   | 0.153476  | 0.336317  | 0.2927    |

Table 14 Values of signal significance for all benchmark points at 100, 500, 1000 and 5000 \(fb^{-1}\) for neutral Higgs \(H\) in the second process

| BP1       | BP2       | BP3       | BP4       |
|-----------|-----------|-----------|-----------|
| Significance \(S/\sqrt{\mathcal{B}}\) at 100 \(fb^{-1}\) | 0.001382  | 3.099     | 12.60     | 0.07411   |
| Significance \(S/\sqrt{\mathcal{B}}\) at 500 \(fb^{-1}\) | 0.00309   | 6.93      | 28.1776   | 0.1657    |
| Significance \(S/\sqrt{\mathcal{B}}\) at 1000 \(fb^{-1}\) | 0.004373  | 9.80064   | 39.8492   | 0.2343    |
| Significance \(S/\sqrt{\mathcal{B}}\) at 5000 \(fb^{-1}\) | 1.01852   | 21.9149   | 89.1055   | 0.5240    |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 100,500,1000\) | 0.000633225 | 0.197228  | 0.3471    | 0.2927    |
| \(\epsilon_{total}\) at \(\mathcal{L}_{int}[fb^{-1}] = 5000\) | 0.37      | 0.197228  | 0.3471    | 0.2927    |

b-parton and the jets. The computation of significance of signal is totally based on the luminosity (Integrated) of 100 \(fb^{-1}\), 500 \(fb^{-1}\), 1000 \(fb^{-1}\) and 5000 \(fb^{-1}\) for all of our profiles of mass distribution. Table 11 shows the signal significance values at each benchmark point, for neutral Higgs \(H\) in the first process at integrated luminosities of 100 \(fb^{-1}\), 500 \(fb^{-1}\), 1000 \(fb^{-1}\) and 5000 \(fb^{-1}\) and total efficiency. Table 12 shows the signal significance values at each benchmark point, for pseudoscalar Higgs \(A\) in the first process at integrated luminosities of 100 \(fb^{-1}\), 500 \(fb^{-1}\), 1000 \(fb^{-1}\) and 5000 \(fb^{-1}\) and total efficiency. Table 13 shows the signal significance values at each benchmark point, for pseudoscalar Higgs \(A\) in the second process at integrated luminosities of 100 \(fb^{-1}\), 500 \(fb^{-1}\), 1000 \(fb^{-1}\) and 5000 \(fb^{-1}\) and total efficiency for the second process. Table 14 shows the signal significance values at each benchmark point, for Neutral Higgs \(H\) in the second process at integrated luminosities of 100 \(fb^{-1}\), 500 \(fb^{-1}\), 1000 \(fb^{-1}\) and 5000 \(fb^{-1}\). The signal significance, plotted versus benchmark points, is shown in Fig. 14 for the first process, and for the second process, it is shown in Fig. 15.
The study aims to investigate the observability of pseudoscalar Higgs A and neutral scalar H in the framework of 2HDM type-I using lepton collider which will operate at the center of mass energy $\sqrt{s}=1000$ GeV. The focus of the study is neutral Higgs pair production at electron positron collider and its fully hadronic decay. The CP even neutral Higgs decays to pair of the bottom quark and the pseudoscalar Higgs decays to Z boson along with neutral heavy CP even Higgs boson. Neutral Higgs is a very unstable particle that decays in no time to pair of bottom quarks. In this work, the predicted pseudoscalar (A) and neutral scalar (H) were examined using Type-I of two Higgs doublet model(2HDM) at SM-like scenario which is the theoretical framework for this study. In 2HDM, few benchmark points (BP) in parameter space were assumed. The main chain process or the signal process is $e^-e^+ \rightarrow AH \rightarrow ZHH \rightarrow jjb\bar{b}b\bar{b}$. The second process is $e^-e^+ \rightarrow AH \rightarrow b\bar{b}b\bar{b}$. At low values of $\tan \beta$, possible enhancements in the couplings of Higgs fermion may occur. At that time, the chain process gives a chance for the signal to take benefit from it. Even though, assumed decay (hadronic) of Z boson may arise many errors and fluctuations in the final results, the calculations due to arising uncertainties form rate of mistagging and the jet misidentification. Therefore, enhancement of this channel completely compensates for fluctuations and errors which arise. Few benchmark points (BP) are supposed at the $\sqrt{s}$ (center of mass-energy) of $1000$ GeV, and for each BP scenario, events are generated separately. By the finalized study of data, it is concluded that presented data analysis is the best way to observe and examine the whole scenario, which are assumed in this study. In the distributions of mass of the Higgs bosons, it can be seen that there exist a significant amount of data and peaks in data of total background near the generated masses, in the assumed luminosities (integrated). A and H Higgs bosons in all considered scenarios are observable when the signal exceeds $5\sigma$, which is the final extracted value of signal significance in accordance with the range of whole mass. Mass reconstruction was performed by the process of fitting functions to mass profiles (distributions). As a result of this process, it is concluded that in all of the assumed scenarios, the finalized reconstructed masses of Higgs bosons are in rational agreement with the generated masses and thereby Higgs bosons (A and H) mass measurements are possible. The presented analysis is expected to

8 Conclusion

The final results for signal significance for the first and second process are shown in Figs. 16, 17, 18 and 19.
Fig. 16  Signal significance corresponding to each benchmark point at integrated luminosities of 500 fb$^{-1}$ for neutral Higgs $H_1$ for the first process.

Fig. 17  Signal significance corresponding to each benchmark point at integrated luminosities of 500 fb$^{-1}$ for pseudoscalar Higgs $A$ for the first process.

Fig. 18  Signal significance corresponding to each benchmark point at integrated luminosities of 500 fb$^{-1}$ for neutral Higgs $H$ for the second process.
work as a tool for the search of predicted neutral Higgs bosons in 2HDM. Till now, simulation results, the center of mass (CMS) energy, and the integrated luminosities are quite promising for the observation of all the assumed scenarios.

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

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