Flavor violating signatures of lighter and heavier Higgs bosons
within Two Higgs Doublet Model type III at the LHeC

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Abstract

We analyze the prospect for observing the lightest and heavier CP-even neutral Higgs bosons($\phi= h$ and $H$) in their decays to flavor violating $b\bar{s}$ (with charge conjugation) at the proposed Large Hadron electron Collider(LHeC), with center-of-mass energy approximately 1.296 TeV, in the framework of the Two Higgs Doublet Model Type-III, assuming a four-zero texture in the Yukawa matrices and a general Higgs potential. We consider scenarios in agreement with the current experimental data of flavor physics constraints and Higgs physics. We consider the charge current production processes: $\nu_e\phi q_f$, with the flavor violating decays of the Higgs bosons, that leads to 3-jets + $E_T$. We demanded exactly two jets, one tagged $b$-jet and one low flavor jet, in the central rapidity region. The remaining jet ($q_f$) has been tagged in the forward regions and this together with the central jet veto (not more than one low flavor jet) are essential criterions to enhance the signal–to–background. We consider the most relevant Standard Model backgrounds, treating $c$-jets separately from light flavor and gluon jets, as well as allowed mistagging. We find that the SM Higgs boson, $h$, would be shown up within the some scenarios of our model, approximately 1-2$\sigma$ at the LHeC, with 100 fb$^{-1}$ of data. We also find that second heavier neutral Higgs boson, $H$, with mass 150 GeV would have 1-$\sigma$ significances. We expect that our finding will show up at LHeC with the designed luminosity, if the latter is upgraded by a factor of 2-3. This leads to significances of 2-3$\sigma$ and hence one can argue that the scenarios of our model could be the most viable extension of the 2HDMs with Flavour Changing Neutral Currents generated at tree level and controlled by the four-zero texture approach in the Yukawa matrices.

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1 Introduction

The Standard Model (SM) is well established by now after finding the Higgs boson at the ATLAS [1] and CMS[2] experiments at Large Hadron Collider (LHC). However, when we want to study some theoretical aspects and outlooks of the SM, for example, lepton number violation (which manifests itself in small but non-zero neutrino masses), small but non-zero flavor violation (in the lepton sector, e.g. $\mu \rightarrow e\gamma$, in the MEG experiments[3], as well as in the quark sector in the B-physics, like Babar[4], Belle[5], and also the top-quark flavor violating decays into charm quark and Higgs bosons). At all them, the SM has to be extended. In general the extensions, namely non-supersymmetric ways, have been invoked by introducing extra scalars singlets and/or doublets. If the number of scalar doublet is two, then the model called the Two Higgs Doublet Model (2HDM) [7, 8]. On the other hand, the phenomenology of 2HDM focussing on the flavor violating Higgs bosons decay branching has been much studied in [9–16]. The finding of Higgs bosons in flavor violating mode at LHC within 2HDM has been subject of interest since long [17–24], in gamma-gamma collider [10], by the ATLAS collaboration in electron-muon channel from $H \rightarrow WW$ [25] at $e^+e^-$ collider [26], at future hadron collider [20], and very recently by the CMS collaboration [27]. The Higgs boson signal with flavor and CP-conserved 2HDM has been studied in [17, 19]. The CP-odd Higgs boson searches within 2HDM has been studied in [28]. The lepton flavor violating (LFV) decays of the Higgs boson studied in various extension beyond SM since long [15, 16, 29–40]. The tri-linear and quartic coupling measurements from the multiple Higgs production within 2HDM has been studied in [41–43]. Also studied in [44] when the Yukawa couplings are the complex. In an effective theory approach, the Higgs boson mediated double flavor violating has been studied in [45]. At the Tevatron the authors [46] looked at LFV Higgs decay, in maximal flavor violation(MxFV) model [47] where the Higgs directly couples to different flavor quarks and studied the same-sign leptons signatures from same-sign top quarks. As the Higgs boson is strongly coupled with the top-quark Yukawas, so the flavor violating signatures is naturally appears in the top-quark sector as well and has been studied [48] and also in the context of the LHeC [49]. The light Higgs boson, with mass less than 60 GeV within 2HDM model has been studied recently [50]. The heavy Higgs boson with masses ranges more than 200 GeV [51] and even after the di-top quark thresholds [24] searched within 2HDM model. However in our work we focusses on heavy Higgs masses below the top-quark.

We particularly motivated by the enhancement of flavor violating quark decays ($\phi \rightarrow b\bar{s}$) of the intermediate mass Higgs bosons (below the top-quark mass) and focus on the feasibility test of all these models at the upcoming Large Hadron electron Collider (LHeC). The LHeC experiment [52] at CERN is a future Deep inelastic scaterring(DIS) experiment at the TeV scale, with center-of-mass energy is around 1.3 TeV. In comparison to the another recently closed at 2007 DIS experiment (around 320 GeV, Hadron-Electron Ring Accelerator(HERA) [6] at DESY with integrated luminosity is around 0.5 fb$^{-1}$, the LHeC deliver integrated luminosity is approximately 100 fb$^{-1}$ and with higher detector coverage. The overall kinematic range accessible at LHeC is 20 times larger than HERA. All these options leads to in-depth studies of the QCD in high-precision and also aid in the search for new particles of beyond SM, including Higgs bosons of multi-Higgs doublet models. Our objective in this paper is to study the feasibility to finding two CP-even neutral Higgs bosons, one is the SM Higgs($h$) and the second heavier Higgs($H$) at the upcoming LHeC and explain within of the Two Higgs Doublet Model.
type III, considering the four-zero texture approach in the Yukawa matrices, as the mechanism that controls the FCNCs (called in the following only as the 2HDM-III).

In the next section we briefly describe the theoretical structure of the 2HDM-III with a four-zero texture embedded in the Yukawa matrices. In Section III we demarcated the allowed 2HDM-III parameter spaces. In Section IV we explain the characteristics of the Higgs boson signal from the charged current production, the most important SM backgrounds and finally we explain the Signal and backgrounds kinematic characteristics and how we adopt a simple cut-based optimization to isolate the Signal. In section V summarize the conclusion.

2 The Higgs-Yukawa sector of the 2HDM type III

In 2HDM, two Higgs scalar doublets has the same hypercharge +1, $\Phi_1^\dagger = (\phi_1^-, \phi_0^*)$ and $\Phi_2^\dagger = (\phi_2^-, \phi_0^*)$, such that both the Higgs doublets couples to same quark flavor. Since a specific four-zero-texture is implemented as a flavor symmetry in the Yukawa sector, namely, now is the mechanism that controls the FCNCs, the discrete symmetries in the Higgs potential are not needed. Then the most general $SU(2)_L \times U(1)_Y$ invariant scalar potential, following [8], can be written as:

$$V(\Phi_1, \Phi_2) = \mu_1^2(\Phi_1^\dagger \Phi_1) + \mu_2^2(\Phi_2^\dagger \Phi_2) - \left(\mu_{12}^2(\Phi_1^\dagger \Phi_2) + \text{H.c.}\right) + \frac{1}{2} \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_5(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_6(\Phi_1^\dagger \Phi_1) + \lambda_7(\Phi_2^\dagger \Phi_2) + \text{H.c.},$$

where all the parameters are assumed to be real, including the vacuum expectation values of the scalar fields so that there is no CP-violation. In general, by putting some discrete symmetry $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$, the scalar potential does not have the contributions of $\lambda_6$ and $\lambda_7$ to get rid of dangerous flavor changing neutral current (FCNC) effects right from the sources. However, when a four-zero texture is embedded in the Yukawa matrices, the FCNCs are controlled and we do not need impose a discrete symmetry in the Higgs potential [9–13].

It has long been proposed that there are four possibilities to satisfy the Paschos-Glashow-Weinberg [53] theorem in the 2HDMs [7, 8]. These are defined as the following: Type I (where one Higgs doublet couples to vector bosons and other to fermions); Type-II (one Higgs doublet couples to up-type quarks and the other couples to the down-type quark); Type-X (termed as “Lepton-specific” where the quark couplings like Type-I and and the lepton couplings like Type-II); Type Y (termed as “Flipped” model, where the Higgs bosons couplings like Type II, and lepton couplings like Type I). With these two scalar doublets, there are eight fields but only five of them are physical scalar (“Higgs”) fields, which correspond to five Higgs bosons: two CP even bosons $h$ (lighter)/$H$ (heavier), one neutral CP-odd boson $A$, and two charged bosons $H^\pm$. The mixing angle $\alpha$ of the two neutral CP -even bosons $h$ and $H$ is another parameter of the 2HDM model. In total, the 2HDM model can be described by the parameters $\alpha$, $\beta$ (where $\tan\beta$ is the ratio of the vacuum expectation values of the two neutral Higgs bosons) and the

\footnote{The $\mu_{12}^2$, $\lambda_5$, $\lambda_6$ and $\lambda_7$ parameters could be complex in general, but for simplicity we assume these parameters are real.}
masses of the five Higgs particles. With this inputs one can estimate all the parameters are present in the scalar potential, to be specifics, the λ’s. These λ’s (together with various scalar mass parameters) are appear in the expression of theoretical constraints like, vacuum stability, unitarity, perturbativity and also of the various electro-weak precision observable (EWPO), for example, the oblique parameters. All these 2HDMs are fully compatible to the SM-like Higgs.

The flavor sector of the 2HDM is an interesting aspect and could be testable in low energy as well as high energy collider experiments. The tests have been carried out in the most general version of a 2HDM with a Yukawa texture of four-zero, which can avoid the main flavor physics constraints \[12, 13\], as this four-zero texture is the mechanism to control FCNCs, by taking the Yukawa couplings proportional to the geometric mean of two fermions masses, \( g_{ij} \propto \sqrt{(m_i m_j)} \chi_{ij} \[54, 55\]. As it was mentioned, a consequence of latter is that the terms of scalar potential with \( \lambda_6 \) and \( \lambda_7 \) should be taken into account. This leads to the tri-linear and quartic self-couplings of the scalar fields \[8, 10\], affects phenomenology in one loop processes and in the collider experiments via the production of di-Higgs, tri-Higgs, and also of decays of Higgs to Higgs bosons. It has been shown that the electro-weak \( \rho \) parameters has large one-loop correction as long as as the mass difference between charged Higgs with CP-even/CP-odd masses are large irrespective of the \( \lambda_6 \) and \( \lambda_7 \). The Yukawa Lagrangian \[5\] is given by

\[
\mathcal{L}_Y = -\left( Y^{u}Q_{L}\tilde{\Phi}_1 u_R + Y^{u}Q_{L}\tilde{\Phi}_2 u_R + Y^{dL}\Phi_1 d_R + Y^{dL}\Phi_2 d_R + Y^{l}\Phi_1 l_R + Y^{l}\Phi_2 l_R \right),
\]

where \( \Phi_{1,2} = (\phi_{1,2}^{+},\phi_{1,2}^{0})^{T} \) refer to the two Higgs doublets, \( \tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^{*} \). The fermion mass matrices after electro-weak symmetry breaking from Eq. (2), namely: \( M_f = \frac{1}{\sqrt{2}}(v_1 Y_{1}^f + v_2 Y_{2}^f) \), \( f = u, d, l \), assuming that both Yukawa matrices \( Y_{1}^f \) and \( Y_{2}^f \) have the four-texture form and are Hermitian \[13\]. After diagonalisation by the following way: \( M_f = V_{fL}^{\dagger} M_f V_{fR} \). Then, \( \tilde{M}_f = \frac{1}{\sqrt{2}}(v_1 \tilde{Y}_{1}^f + v_2 \tilde{Y}_{2}^f) \), where \( \tilde{Y}_{i}^f = V_{fL}^{\dagger} Y_{i}^f V_{fR} \). One can have a better approximation for the product \( V_q Y_n^q \), by expressing the rotated matrix \( \tilde{Y}_n^q \) as

\[
\begin{aligned}
\tilde{Y}_n^q_{ij} &= \sqrt{\frac{m_i^q m_j^q}{v}} \left[ \chi_{nij}^q \right] = \sqrt{\frac{m_i^q m_j^q}{v}} \left[ \chi_{nij}^q \right] e^{i\varphi_{nij}},
\end{aligned}
\]

where the \( \chi \)'s are unknown dimensionless parameters of the model. Following \[12, 13\], one can have the generic expression of the Higgs bosons with the fermions:

\[
\mathcal{L}_{H_{ij}^f} = -\left( \frac{\sqrt{2}}{v} \bar{u}_i (m_d, X_{ij} P_R + m_u Y_{ij} P_L) d_j H^+ + \frac{\sqrt{2} m_i}{v} Z_{ij} \bar{q}_L H^+ + H.c. \right) - \frac{1}{v} \left( \tilde{f}_i m_f h_{ij}^f h_j^0 + \tilde{f}_i m_f h_{ij}^f h_j^0 - i \tilde{f}_i m_f A_{ij}^f f_j \gamma_5 A^0 \right),
\]

(4)
To get the benchmarks, we have taken into account the recent experimental bounds from the flavor physics \cite{12, 13} – in the Higgs decays with flavor violation. We show that in different scenarios of the 2HDM-III, specific incarnations where the leptonic decay branching is large, we look for an enhancement at tree level. Here, we consider three different incarnations for the 2HDM-III (except the lepton conjugation) is possible. At the end we look for Higgs bosons in these particular flavor violating signatures, in twelve scenarios shown in Table 1, at the high energy collider experiments, namely at LHeC. We study the following scenarios:

- **Scenario Ia**: 2HDM-III as 2HDM-I, with the couplings $\phi f f$ given by $g_{2HDM-III}^{\phi ff} = g_{2HDM-I}^{\phi ff} + \Delta g$ and $\cos(\beta - \alpha) = 0.1$.

- **Scenario Ib**: the same that the scenario Ia but with $\cos(\beta - \alpha) = 0.5$.

- **Scenario Ia**: 2HDM-III as 2HDM-II, namely, the couplings $\phi f f$ given by $g_{2HDM-III}^{\phi ff} = g_{2HDM-II}^{\phi ff} + \Delta g$ and $\cos(\beta - \alpha) = 0.1$.

- **Scenario Y**: 2HDM-III as 2HDM-Y, namely, the couplings $\phi f f$ given by $g_{2HDM-III}^{\phi ff} = g_{2HDM-Y}^{\phi ff} + \Delta g$ and $\cos(\beta - \alpha) = 0.1$.

To get the benchmarks, we have taken into account the recent experimental bounds from the flavor physics \cite{12, 13} – $B \rightarrow \tau \nu$, $D \rightarrow \mu \nu$, $D_s \rightarrow \mu \nu$, the semileptonic transition $B \rightarrow D\tau \nu$, the inclusive decay $B \rightarrow X_s \gamma$, $B_0 - B_0$ mixing, $B_s \rightarrow \mu^+ \mu^-$ and the radiative decay $Z \rightarrow b\bar{b}$. We have also imposed the perturbativity, electro-weak and unitarity constraints \cite{3, 59}. In all the constraints mentioned above the charged Higgs masses are the utmost crucial parameters, within 2HDM, as it replaces the SM $W$-exchange diagrams. We have also taken the allowed Charged Higgs masses from flavor and electro-weak constraints \cite{11, 12, 60, 62}. The Higgs boson masses with currents low energy constraints has been studied very recently \cite{63, 64}.
Table 1: The model parameters for few optimistic benchmark points in 2HDM-III scenario Ia, Ib, IIa, Y. The \(bs\) stands for \(\text{BR}(\phi \to b\bar{s} + b\bar{s})\), where \(\phi = h, H\) units of \(10^{-2}\), where as \(\sigma.bs\) stands for the cross-section multiplied with the branching ratios at the LHeC collider in units of \(fb\). We have analyzed only the Benchmarks where the \(\sigma.bs\) is greater than 0.15 \(fb\), so that at least 15 events is produced in the real collision for 100 \(fb^{-1}\).

### 3 The 2HDM model parameters and benchmark

Taking into all the constraints mentioned in sec.2, we concentrated on three 2HDM scenarios where the number of Higgs signal event in the \(bs\) mode is large enough. The \(\sigma.bs\) is shown in Table 1. We only simulated benchmarks where \(\sigma.bs\) is more than 0.15 \(fb\). So that for integrated luminosity of 100 \(fb^{-1}\) we can start with at least 15 events.

### 4 Numerical Analysis

In this section we describe first the production of Higgs signal. We then discuss the most important SM backgrounds and the different kinematical selections for the events.

#### 4.1 Production of Higgs bosons signals

We consider the leading production processes\(^3\) of Higgs boson: \(\nu, \phi q^\pm\), where \(\phi = h, H\); and \(q\) is the low-flavor quarks (i.e., \(u, d, s, c\)) and gluon(\(g\)). We assume that \(\phi\) is dominantly decaying into \(b\bar{s}\) (with charge conjugation) channel. So both of our signals, lighter Higgs as well as heavier Higgs, contains three jet (one jet is forward and two jets are central), missing Energy and no-lepton. Out of two central jets, one is \(b\)-tagged jet and other is low-flavored jet. We will see

\(^3\)The charged-current production is approximately 5 times larger than the neutral current production. Moreover, the neutral current production contains a electron and since we are vetoing lepton in this particular analysis we consider only the charged processes.
that with invariant masses corresponding to the respective Higgs masses are the consequences of Higgs flavor violation. We estimated the parton level signal cross-sections with flavor-violating of the 2HDM-III, using th implementation on CalcHEP v3.4.7 [65] Matrix Element calculator. This implementation also calculate the branching ratios of the Higgs bosons(\(\phi\)), into \(b\bar{s}\). For estimating the cross-sections at the LHeC [52, 66–70], we consider electron-beam, \(E_e = 60\) GeV and proton beam, \(E_p = 7000\) GeV, corresponding to the center-of-mass energy approximately \(\sqrt{s} = 1.296\) TeV. The integrated luminosity is \(100 fb^{-1}\). To estimate the event rate at parton level we applied the following basic pre-selections:

\[
p_T^q > 15.0 \text{ GeV}, \Delta R(q, q) > 0.4
\]

where \(\Delta R = \Delta \eta^2 + \Delta \phi^2\), where \(\eta\) and \(\phi\) are the pseudo-rapidity and azimuthal angle respectively. We take \(m_t = 173.3\) GeV as pole mass. All the masses and mass parameters in our analysis are in GeV. We set the renormalization and factorization scale at Z-boson masses (approximately the momentum transfer scale for Signal) and set CTEQ6L[71] parton distribution function, with \(\alpha_s\) (the strong coupling constant) evaluated consistently at all stages (PDFs, hard scattering and decays). We took all the low flavored quarks, gluon and also the b-quark fluxes inside proton. We also considered the appropriate flavor-mixing where appropriate using the present values. The top-quark and W-boson are allowed to be decayed freely and has been taken care once the event is fed into PYTHIA [72]. The signal cross-sections, branching ratios and cross-sections multiplied with the branching ratios, are tabulated in Table.1. The signal processes in our considerations are unique kinematic profiles. In particular the final state quarks transverse momentum is less than the mass of the vector bosons, its energy is very high with small angle to the beam directions, i.e., high forward rapidity. The rapidity of the forward jet (\(J_f\)) is shown in the right panel of Fig.2. These processes [73] and the kinematic features to discover the Higgs boson has been studied since long [74]. The parton level study has been performed within SM recently in [75]. In the context of beyond SM the cross-section estimates with taking into the NLO factor has been performed in [76] but no signal and background studies. However dedicated simulation in the event generator level has not been done extensively and we focus on this aspects and most importantly discovering two Higgs bosons simultaneously in the flavor-violating modes.

### 4.2 Backgrounds

There are mainly two groups of backgrounds to our Higgs signal. The charged-current backgrounds: \(\nu t\bar{b}, \nu b\bar{b}j, \nu b2j, \nu 3j\) and the photo-production backgrounds: \(e^{-}b\bar{b}j\), \(e^{-}t\bar{t}\). For estimating the cross-sections of these SM backgrounds, we used the same pre-selections like signal, Eqn.9 and identical conventions and parameter sets. The expected number of events for \(100 fb^{-1}\) integrated Luminosity are given in the third column of Tables.2. We generated these events using CalcHEP v3.4.7 [65].

### 4.3 Simulations

We passed the CalcHEP v3.4.7 [65] generated parton level event on to PYTHIA v.6.408 [72], which handles the parton shower (both initial and final), hadronization, heavy hadron decays etc. The final state radiation smears the four-momentum of the jets, thus the invariant mass of
the Higgs boson signal is less than the actual values considered in the event. We also took the experimental resolutions of the jet angles and energy using the toy calorimeter PYCELL, in accordance with the LHeC detector parameters, given in PYTHIA. This has some non-trivial effect since we used the invariant mass to isolate the Higgs signal. In our study we considered the LHC type calorimeter for the LHeC. Although in reality this is not the case, for example, unlike ATLAS and CMS the electro-magnetic and the hadronic calorimeter at the LHeC is not symmetric. However, since we are not doing detector simulation and also not considering cracks in the detectors, we applied symmetric large rapidity coverage for jets and leptons in our analysis. We expect that these assumptions hardly alter our findings. The detector parameters in the toy calorimeter module PYCELL are set according to the LHeC detector [68]. Specifically, we assume large calorimeter coverage $|\eta| < 5.5$, with segmentation (the number of division in $\eta$ and $\phi$ are 320 and 200 respectively) $\Delta \eta \times \Delta \phi = 0.0359 \times 0.0314$. Further, we have used Gaussian energy resolution [66] for both leptons ($\ell = e, \mu$) and jets (labelled as $j$), with

$$\frac{\Delta E}{E} = a \sqrt{E} \oplus b$$

(10)

for jet $a=0.32$, $b=0.086$; and for lepton $a=0.085$, $b=0.003$, where $\oplus$ means addition in quadrature. We have used a cone algorithm the for the jet-finding algorithm, with jet radius $\Delta R(j) = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.5$. Calorimeter cells with $E_{T,\text{min}}^{\text{cell}} \geq 5.0$ GeV are considered to be potential candidates for jet initiators. All cells with $E_{T,\text{min}}^{\text{cell}} \geq 1.0$ GeV were treated as part of the would-be jet. A jet is required to have minimum summed $E_{T,\text{jet}}^{\text{jet}} \geq 15$ GeV and the jets are ordered in $E_T$. Leptons ($\ell = e, \mu$) are selected if they satisfy the requirements: $E_T^{\ell} \geq 15$ GeV and $|\eta^{\ell}| \leq 3.0$. In our jet finding algorithm we includes leptons as parts of jets. Finally we separate them, putting some isolation criterion as follows: if we find a jet near a lepton, with $\Delta R(j-\ell) \leq 0.5$ and $0.8 \leq E_T^{j}/E_T^{\ell} \leq 1.2$, i.e. if the jet $E_T$ is nearly identical to that of this lepton, the jet is removed from the list of jets and treated as a lepton. However, if we find a jet within $\Delta R(j-\ell) \leq 0.5$ of a lepton, whose $E_T$ differs significantly from that of the lepton, the lepton is removed from the list of leptons. This isolation criterion mostly remove leptons from $b$ or $c$ decays. We reconstructed the missing energy ($E_T$) from all observed particles and shown in left panel of Fig. We have also calculated the same from the energy deposition in the calorimeter cells and found consistency between these two methods. Only jets with $|\eta^j| < 2.5$ and $E_T^j \geq 15$ GeV “matched” with a $b$-flavored hadron ($B$-hadron), i.e. with $\Delta R(j, B-\text{hadron}) < 0.2$ is considered to be “taggable”. We assume that these jets are actually tagged with probability $\epsilon^b = 0.50$. We also adopted mistagging of non-$b$ jets as $b$-jets and treated $c$-jets differently from the gluon or low flavor jets. A jet with $|\eta^j| \leq 2.5$ and $E_T^j \geq 15$ GeV matched with a $c$-flavored hadron ($C$-hadron, e.g., a $D$-meson or $\Lambda_c$-baryon), i.e., with $\Delta R(j, C-\text{hadron}) < 0.2$, is again considered to be taggable, with (mis)tagging probability $\epsilon^c = 0.10$. Jets that are associated with a $\tau$-lepton, with $\Delta R(j, \tau) \leq 0.2$, and all jets with $|\eta^j| > 2.5$, are taken to have vanishing tagging probability. All other jets with $E_T^j \geq 15$ GeV and $|\eta^j| \leq 2.5$ are assumed to be (mis)tagged with probability $\epsilon_{u,d,s,g} = 0.01$. These efficiencies follow recent LHeC analysis [23].

The analysis strategy has been adopted from our earlier work [17]. We have adopted a simple cut-based method for signal enhancement and background rejections. We have chosen the following selections, and applied cumulatively, for the signal from $h(H)$:

- **a(A):** We first selected that the event must contain at least three jets (same). The
### Table 2: Expected number of events after different combinations of cuts for signal and backgrounds at the LHeC with 100 fb$^{-1}$ integrated luminosity for $m_h=125$ GeV. SimEvt stands for the actual number of events analyzed in the Monte Carlo simulations. RawEvt stands for the number of events with only the generator–level cuts (9) imposed; for the signal as well as for the actual number of events analyzed in the Monte Carlo simulations. RawEvt stands for background events $B$ for 100 fb$^{-1}$ of data after all cuts mentioned in the “i” column.

| Proc | SimEvt | RawEvt | A   | B   | C   | D   | E   | F   | G   | H   | I   | S   |
|------|--------|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Ib2  | 55K    | 32.8   | 23.6| 9.2 | 7.3 | 6.1 | 5.8 | 2.0 | 1.7 | 1.5 | 0.9 | 0.07 |
| Ib5  | 60K    | 51.6   | 37.0| 145.0|114.4|94.7 |90.9 |30.3 |24.6 |21.1 |13.5 |1.1  |
| Ib30 | 80K    | 75.9   | 520.6|210.7|163.3|134.2|129.2|42.8 |31.2 |23.1 |14.2 |1.17 |
| Hb2  | 50K    | 16.7   | 11.8| 4.8 | 3.7 | 3.1 | 3.0 | 0.9 | 0.7 | 0.5 | 0.3 | 0.02|
| Yb5  | 50K    | 22.0   | 15.4| 6.1 | 4.7 | 3.9 | 3.7 | 1.3 | 0.9 | 0.7 | 0.5 | 0.04|
| Yb30 | 50K    | 51.8   | 36.3| 14.8|11.7| 9.7 | 9.3 | 3.0 | 2.2 | 1.6 | 1.1 | 0.09|
| νtb  | 100K   | 50712.1|28388.4|15293.7|9845.0|8144.2|7532.7|2982.1|2058.0|652.2|139.6|
| νbbj | 500K   | 14104.6|6122.8|3656.7|1858.5|1787.1|1601.0|257.5|152.5|85.2 |15.1 |
| νb2j | 90K    | 18043.1|8389.2|3013.0|1691.5|1445.5|1373.7|389.5|206.1|77.2 |11.3 |
| ν3j  | 300K   | 948064.2|410393.4|15560.9|0.0 |0.0 |0.0 |0.0 |0.0 |0.0 |0.0 |$\sqrt{B}=13.1$|
| ebbj | 115K   | 256730.1|55099.8|36353.6|12659.8|1432.0|200.7|54.1 |24.8 |18.0 |4.5  |
| ett  | 130K   | 783.3  | 685.0|384.5|265.9|179.3|26.2 |11.6 |10.5 |3.9 |0.3  |

Table 3: Same as of Table 2 but for $m_H=130$ GeV. The criterion for jets and $b$-tagging are same, so the number of events in column $A$ and $B$ are same for all SM backgrounds.

distributions of number of jet ($N_{jet}$) is shown in the left panel of Fig 1. For the lighter Higgs, $h$, all the Signal benchmarks, the efficiencies are approximately 70%. $t\bar{b}$ has efficiencies approximately 56%, where $2bj$ and $3j$ events contains approximately 45%, where as $b2j$ is approximately 47%, the less efficiencies are for the photo-production $e2t$ is approximately 20% (falls due to the isolation criterion), where as for $e2t$ the jet efficiencies

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4Unless mentioned otherwise, all the efficiencies quoted hereafter with respect to the previous selection.
are higher as presence of two top-quarks leads to two b-quarks and the probability of having two jets from W-boson decay itself approximately 91%, thus out of 4-jets in 91% events, the probability is having at least three energetic jets is reduced by 4%, which leads to approximately, 87%. However, as we will see in a while that the presence of the electron, in the photo-production leads to that backgrounds to a low level.

- **b(B):** We demanded at least one b-tagged jet with the inclusion of proper mis-tagging(same).

The distributions of number of b-tagged jet \( N_{b\text{-tag}} \) is shown in the right panel of Fig. 1. For the lighter Higgs, \( h \), all the Signal benchmarks, the b-tagging efficiencies are approximately 40%. In fact all our Signal benchmarks contains at least one b-quark, and since we adopted the \( \epsilon_b=0.50 \), the 10% lowering is somewhat realistic and due to the fact that not all b-quark in the signal is eligible for the b-taggable criterion adopted in our analysis. For heavier Higgs Signal benchmarks also the similar efficiencies are show-up. In case of \( t\bar{b} \), the event containing at least one b-tag jet is approximately 54%, is greater than the Signal, as this event contains at least two b-quark in the parton level, so due to combinatorics (other than the fact of mis-tagging of low flavored quark jet from W-boson decays) the probability of one b-tag is more. The probability of 2bj is approximately 60%, approximately 6% larger than \( t\bar{b} \) due to the fact that unlike \( t\bar{b} \) presence of one b-quark and one low flavored jet are present in the hard processes itself. \( b2j \) efficiencies follows similar or little less than the Signal due to the fact that the taggable rapidity is more central, where the jets are more likely forward in the basic hard processes. The efficiencies of \( e2t \) is approximately 2% larger than \( t\bar{b} \) mainly due to the contributions from the mis-tagging from one extra W, i.e, two extra jets. The efficiencies of \( 3j \) is approximately 4%, which seems somewhat consistent with the mis-tagging efficiencies (1.0% from low-flavored jets
Figure 1: Scenario Ib with the parameter X=-Y=30. The number of jets ($N_{jet}$) in the left panel and the number of $b$-tagged jet (with the inclusion of mis-tagging) in the right panel for Signal ($m_H=150$ GeV) and all the SM backgrounds. For other Signal events, the distributions profile are very similar, except the fact that the number of jets as well as the $b$-tagged jets are little larger for heavy Higgs bosons. See the fourth(fifth) column for their efficiencies with selections applied in a(b) and A(B) for lighter and heavier Higgs bosons respectively.

and from $c$-jet it is 10%) with the combinatorics.

- **c(C):** We demanded at least two central jets, with $p_T > 30$ GeV (25 GeV, 20 GeV, 15 GeV for $m_H=130$, 150 and 170 GeV\) in the pseudo-rapidity range $|\eta| < 2.5$. One of the central jet must be a $b$-tagged jet and we demanded only one $b$-tagged jet(same). For the lighter Higgs, $h$, all the Signal benchmarks, $tb$ has survived approximately 65% of the event since all these processes naturally three jet in the events. $e2bj$ and $2bj$ is reduced to approximately 35% and 50% respectively mainly due to the demanding that with respected to the b(B) above, we demanded one $b$-tagged jet only. The diagrams of $tb$ and $e2t$ reveal that these two events more central, because of the presence of one top-quark in the central region. The efficiencies is larger in $e2t$ is mainly the contributions from additional top-quark. Although in $2bj$ the probability is presence one $b$-tagged in the central region is larger, however the efficiencies is reduced to 12% due to partly possibility of more than one $b$-tagged and for $Wb$ the value is mainly due to the hadronic branching fraction and also that the $b$-tagged jet is not necessary central. In case of $e2bj$ the efficiencies is 35%, this suffers mainly due to the centrality criterion. For $3j$ none of the events survived this selections criterion. The efficiencies pattern discussed above

\[^5\text{Since the cross-sections become smaller with increasing the Higgs masses, we lowered the central jets } p_T.\]
are somewhat true for heavier Higgs bosons, $H$, except the fact that in case of heavier Higgs bosons we used slightly softer selections on the transverse momentum. Thus the efficiencies are increasing with softer $p_T$ selection for Signal benchmarks and as well as the backgrounds.

- **d(D):** The missing transverse energy ($E_T > 20$ GeV) is applied (same). The distributions is shown in the left panel of Fig.2. For all the signal benchmarks (lighter as well

![Image](image-url)

Figure 2: The missing energy ($E_T$) (left panel) and the rapidity profile of forward jet ($\eta_j$) (right panel) for signals and SM backgrounds. The $E_T$ distributions for all other signal benchmarks, $tb$ are not shown as they are very similar to the signal distributions of $m_H=150$ GeV for scenario Ib with $X=-Y=30$ (shown in thick solid, where as the thin solid is for $m_H=125$ GeV for scenario Ia with $X=-Y=30$). The rapidity distributions profile for $m_H=130(170)$ GeV is very close to the $m_H=125$ GeV($m_H=130$ GeV) shown in thin solid, except for massive Higgs the peaks shift in the left-side. Also rapidity distribution profile for $e2bj$ is somewhat similar to the $m_H=125$ GeV.

heavier Higgs bosons) $t\bar{b}$ and $b2j$ the efficiencies is approximately 83%. The sources of neutrino and the event structures of these two processes are very similar, so thus the efficiencies, except the fact that the top-quark decays produced either neutrino (pure sources of missing energy and in that case, the selection a(A) mentioned above already removed large fraction of that) or quark (where smearing of jets and mis-measurement is the main sources). For $2bj$ the efficiency is approximately 96%. This selections is crucial to suppress the photo-production processes: $e2bj$ and $e2t$. In case of $e2bj$ only 12% events survived. For $e2t$ the presence of two W-bosons and its decay into leptonic mode would be the sources of missing energy thus not affected very much.
• **e(E):** A lepton (e or μ) veto with $p_T > 20$ GeV and $\eta < 3.0$ is applied (same). For the lighter Higgs signal benchmarks, the efficiencies for this selection is approximately 96%. Only 4% events contain at least one lepton which is coming from the semileptonic decays of the B-hadrons, D-meson and which passes the isolation criterion and somewhat realistics. The efficiencies for $2bj$ and $b2j$ are somewhat close to the signal benchmarks, as these processes also not having explicit lepton in the events. The $tb$ event has the efficiency of 93%, approximately 3% more than the Signal, as here the top-quark decays can leads to one bottom quark and if the hard-processes bottom quarks has more central, the requirement of $c(C)$ satisfied and there is no problem of having a lepton from $W$-boson. And we expect that this happen for the 3% event sample. In the photo-production processes, $e2bj$ and $e2t$ both contain hard lepton, so only 15% events survived with this lepton veto. For heavier Higgs masses, the efficiencies are somewhat similar like the lighter Higgs boson masses cases. Only difference is that since the applied $p_T$ is lower for heavier Higgs masses, the probability of having a lepton in the event is higher, thus the veto efficiencies are smaller, except two photo-production processes.

• **f(F):** In the central region, defined above $c(C)$, we reconstruct the invariant mass of one $b$-tagged jet with all other jets, $M_{bj}$. We have chosen the best combinations, where, the absolute difference $|M_{bj} - M_{h(H)}|$ is minimum. We called these jets are the candidate jets of the lighter (heavier) Higgs boson. We have selected events with 15 GeV mass windows with respect to the corresponding Higgs boson masses. The distributions of $M_{bj}$ is shown in the left panel of Fig.3. It seems that the di-jet invariant masses of BP-Ia30 Signal benchmarks (with $m_h=125$ GeV) has its peaks around 115 GeV. The distribution for $tb$ has peak around that of signal $m_t=125$ GeV. The di-jets from the signal as well as $b$-jet and low flavored jets from the central top-quark decays, which constitutes the di-jet invariant masses, leads somewhat same mass scales and shows in their respective distributions. These shows in their efficiencies which is approximately 40% for both. The distribution of $b2j$ is flat as there is no correlations for the correct di-jet candidates. Please note that $b2j$ has W-boson exchanged diagrams, so possibilities of a di-jet invariant mass expected to be show peaks at $M_W$, however the possibility is very small, mainly due to low mis-tagging efficiencies and the centrality criterion. However in case of $2bj$, where the $Z$-boson is present in the diagram, and $Zbb$ vertex as well as the higher tagging efficiencies allows to show up around 80 GeV (approximately 10 GeV less than $M_Z$ due to jet energy smearing) see the left-panel of Fig.

In case of $e2t$, like $t\bar{b}$, has also correlated di-jet candidates, but the energy scale is higher, so the peak shift higher side. The efficiency is approximately 45%, little larger than the Signal and $t\bar{b}$. The distributions of $b2j$ and $e2bj$ are flat and the efficiencies are same, approximately 28%. This particular selection suppresses $2bj$ events more severely, which is approximately 15%. For heavier Higgs bosons the distributions shows the rapid falls and so by applying the mass window cuts, only the left part of the distributions contributes. This shows in their Signal efficiencies, which are approximately 32%, 23% and 18% for $m_H=130,150$ and $170$ GeV respectively.

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6The peaks always show-up to the left side of the actual masses due to jet energy smearing and the shift depends on the jet-cone size.
The SM backgrounds do not show up the distributions at the higher side, thus for heavier Higgs masses and their mass window selection suppresses more the backgrounds. As an example, in case of $e2t$ which is somewhat higher energy scales than all other SM backgrounds, the efficiencies drops from 40%, 12% and 4% for $m_H=130, 150$ and 170 GeV respectively. In case of $tb$ the efficiencies (please see the Tables 2,3,4 and 5) drops from 30%, 8% and 2% respectively. In case of $2bj$ the values are 14%, 10% and 5%. For $e2bj$, the values are 20%, 10% and 7% respectively. For $b2j$ these are 25%, 12% and 5% respectively.

![Figure 3](image.png)

Figure 3: The di-jet invariant mass, one $b$-tagged and one low-flavored Higgs candidates, $M_\phi = M_{bj}$ (left panel) and three-jet invariant mass, together with the forward jet, $M_{\phi j_f}$ (right panel). The mass peaks of Higgs signal($M_\phi$) corresponds to $m_h=125$ (thin black) for scenario Ia, $m_H=150$ (thick black) and 170 (thin black) for scenario Ib from left to right. All them using the parameters $X = -Y = 30$. The distribution for $m_H=130$ is not shown but it lies in between $m_h = 125$ and $m_H = 150$. Among all SM backgrounds, only $2bj$ shows a prominent peaks from the Z-boson. $M_{\phi j_f}$ represent the overall energy scale of the hard-scattering.

- **g(G):** We demanded the remaining leading jet in the event with $p_T > 25$ GeV, with $-5.5 < \eta < -0.5 (-1.0)$ (these values are chosen by seeing the distribution, see the right panel of Fig 2) and termed as the forward tagged jet ($j_f$). This forward jet lies very close to the direction of the incoming proton like the vector boson fusion (VBF) processes for Higgs production. In contrast to VBF, instead of a jet with large rapidity gap with the forward jet, in our signal we have neutrino. The more massive the Higgs is, the energy of the forward jet is becoming less and it lies more close to the proton direction, i.e., larger rapidity. This reflects in the right panel of Fig 2. The thick (thin) solid curves corresponds to $m_H=150$ GeV ($m_h=125$ GeV). For lighter Higgs boson, $m_h = 125$ GeV, the efficiencies

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13
is approximately 80% or more. For $e2t$ the efficiencies is almost 90%, twice as that of $e2bj$, as there is more than twice probability to have a forward-jet from top-quark decays.

- **h(H):** The invariant mass of the Higgs boson candidate jets with the forward tagged jet, which is somewhat the overall energy scale of the hard-scattering, $m_{hjj}$ ($m_{Hjj}$) > 190 GeV (190 GeV, 210 GeV, 230 GeV for $m_{H}$=130, 150 and 170 GeV respectively.) The distributions shows in the right panel of Fig.3. For lighter Higgs boson, $m_{h}$=125 GeV, except few cases, the efficiencies is approximately 80%. This forward jet should not be a b-jet. So, in $t\bar{b}$ and $e2t$ where the forward b-tag jet is more probable, the efficiencies is lower approximately by 32% and 37%. It is clear from the right panel of Fig.3 that the three-jet invariant mass distributions of $b2j$ peaks around 140 GeV or so. The same for $t\bar{b}$, $e2t$, $2bj$, $e2bj$ and the Higgs Signal with $m_{h}$=125 GeV shows somewhere around 180 GeV. So, for $m_{h}$=125 GeV, the efficiencies somewhat 80%. The heavier Higgs bosons, $m_{H}$ = 150(170) GeV, the distributions shown in the thick(thin) solid curve in the right panel of Fig.3 and peaks around 220(260) GeV. The selection cuts for these two Higgs bosons are 210 and 230 GeV respectively. With larger selection for this two heavy Higgs Signal suppresses more SM backgrounds than the Higgs Signal with $m_{h}$=125 GeV and $m_{H}$ = 130 GeV. For example, in $t\bar{b}$ cases, the most dominant background, for $m_{h}$=125 GeV, and $m_{H}$=130, 150,170 GeV, the events survived are approximately 652, 618, 195 and 75 respectively. For other SM backgrounds similar pattern follows thus the overall SM backgrounds is reduced. However this overall suppression will not help alone to have a larger Significances as the Signal rate itself suppressed with the heavier Higgs masses.

- **i(I):** Finally we required only one low flavored jet in the central regions (same).

This selection is called the central jet veto and has severe impact on the processes having more jets in the central rapidity region, other than the Higgs candidates jets. Please recall that our Higgs Signal candidates jets, taken care in f(F) above, are central by the event kinematics. Not only the Signal, also the dominant SM backgrounds, $t\bar{b}$. For lighter SM Higgs, in Table.2, approximately 35-40% events having central jet other than Higgs candidate jets, thus only 60-65% events are survived. For $t\bar{b}$, $\nu b2j$, $\nu 2bj$ the efficiencies are 22%, 18% and 14%. Among all the SM backgrounds, $e2t$ has more number of jets (see the distributions in the left-panel of Fig.11) thus the probability of having a central jet is more so this selections suppresses this background severely, approximately by 93% (for all the Higgs cases, see Tables 2,3,4 and 5).

After the cumulative selections from a–i, discussed above, we find that for SM Higgs, $m_{h}$=125, the final number of events are somewhat 15-30 only for Type-Ia and Type-Ib and for large values of $\tan\beta$. The total SM background events is approximately 170. The charge-currents backgrounds, $\nu t\bar{b}$, $\nu bbj$ and $\nu b2j$ are the dominant and only 3% of the total backgrounds from $e\bar{t}$ photo-production. These leads to maximum significances approximately 2.2 $\sigma$ for Type-Ia with $\tan\beta$=30. For Type-Ib, the significances is approximately 1.4 $\sigma$. The significances for Type-IV and Type-IIa are less than one. Thus one can expect that Type-Ia and Type-Ib with large value of $\tan\beta$ favors re-discovering the SM Higgs boson.

Please note that the efficiencies is relative to the previous selection, so more the cumulation the actual efficiencies are less likely to match to the individuals. One can estimate the individual efficiencies from respective distributions.
We searched the second CP-even neutral Higgs bosons, with masses \( m_H = 130, 150 \) and \( 170 \) GeV, in the same model 2HDM parameter spaces. After the cumulative selections from A-I, the maximum number of Signal events for \( m_H = 130 \) GeV is approximately 15 and only for 2HDM Type-Ib with \( \tan \beta = 15 \) and 30. The total SM backgrounds is approximately 150. So the maximum significances is approximately 1.2 \( \sigma \). For \( m_H = 150 \) GeV, the number of Signal events is approximately 8, and the SM backgrounds reduces to approximately 60; leads to significances approximately 1.0 \( \sigma \). For \( m_H = 170 \) GeV, the raw events is approximately 20 to start with, and at the end the count is only 1.8. The total SM backgrounds is approximately 30, leads to significances approximately 0.1 \( \sigma \).

5 Conclusions

After the discovering of SM Higgs boson at LHC, it is well motivated to look for more Higgs bosons which appears in the model beyond SM. And also in the collider front, not only at LHC also the future proposed collider, such as LHeC. In this analysis we consider 2HDM type III in the scenarios Ia, Ib, Iia and Y, where SM Higgs is part of the scalar sector always, and next massive CP-even Higgs bosons both are accessible at the LHeC energy. We assume that both of them are decaying into flavor violating mode (\( \phi \rightarrow b \bar{s} \)). We selected few model benchmarks where the products of cross-sections and the flavor violating branching ratio is large enough to produce some handful events to look for both signatures and simultaneously. We studied the three-jets and missing energy channel, \( 3j E_T \), from the charge-current production of \( \nu_c \phi q_f \), where \( q_f \) is the forward jet with large rapidity, and other two jets coming from the flavor violating decay \( \phi \rightarrow b \bar{s} \). We demanded one central jet must be a \( b \)-tagged jet with the inclusion of the proper mis-tagging from low flavored and gluon jets. We considered the most dominant SM backgrounds, charged-currents: \( \nu t \bar{b}, \nu bbj, \nu b2j \) and \( \nu 3j \); and photo-production: \( e^{-}bbj \) and \( e^{-}t \bar{t} \).

We performed a full hadron–level Monte Carlo simulation using the PYTHIA v.6.408 \[72\], event generator and its PYCELL toy calorimeter accordances with the LHeC detector parameters. We carefully implemented \( b \)-tagging, including mistagging of \( c \)-jets or light flavor or gluon jets.

The signals under consideration do not have lepton, so we applied lepton veto. The charged-current production have naturally missing energy due to the presence of neutrinos but no lepton. However, the photo-production processes has lepton but no direct missing energy (except the mis-measurements from the jets and smearing), thus the missing energy selection together with the lepton veto suppressed the photo-production backgrounds to a large extent.

The kinematics of this particular signal is very interesting from the fact that the Higgs bosons produces in the central rapidity region and its decay daughters one \( b \)-jet and one non-flavored jet are also central. We reconstructed the invariant mass of this two jets and selected events only if the masses within the 15 GeV windows of the respective Higgs mass of the signal benchmarks. This selection reduces SM backgrounds to a large extent and the invariant mass ensures the Higgs flavor violating decays. For massive Higgs bosons, although the signal events becomes low, with the mass window selections backgrounds suppression are even more.

As a next step of selection, we identify the most energetic low-flavored forward jets (by

Please note that our selection cuts applied above are not optimized. An increase of the luminosity is an easy solutions from phenomenological perspective. However, adopting multivariate analysis technique must be a better discriminator of Signal from backgrounds.
seeing the rapidity profiles) and calculates the invariant mass with that jet together with flavor violating Higgs candidates jets. These three-jet invariant masses somewhat gives the overall energy scale of the hard-scattering. Again more massive is the Higgs this selection helps to suppress more SM backgrounds, in particular $\nu t\bar{b}$ and $et\bar{t}$, but the Signal becomes lower.

At the end, most important we applied the central jet vetos, i.e., to say that we required one low flavored central jets only. This suppresses SM background with large multiplicity events, for example, $\nu t\bar{b}$ and $et\bar{t}$.

After all the selections, with 100 fb$^{-1}$ of data, we found that the SM Higgs boson, $h$, would be show-up within the 2HDM-III in the scenarios called in the work: Ia, Ib with $X = -Y = 15$ or 30, with approximately 1-2$\sigma$. The heavier neutral Higgs boson, $H$, with masses 150 GeV would have 1-$\sigma$ significances in large $X$ and only for scenario Ib. The significances quoted above will be enhanced if the proposed luminosity is increased by a factor of two or three. We adopted a simple cut-based method in this analysis. One would invoke more complex discriminators to enhance the significances within the designed luminosity.

In either of the cases, adopted complex discriminator and/or the luminosity upgradation, we expect that our finding will show-up at LHeC. Hence one can argue that the scenario Ib of the 2HDM-III is the most viable extension of the 2HDMs from the flavor violating scalar sectors.

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