Light charged Higgs boson production at the Large Hadron electron Collider

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We study the production of a light charged Higgs boson at the future Large Hadron electron Collider (LHeC), through the process $e^- p \rightarrow \nu_e H^- q$ considering both decay channels $H^- \rightarrow b\bar{c}$ and $H^- \rightarrow \tau\bar{\nu}_\tau$ in the final state. We analyse these processes in the context of the 2-Higgs Doublet Model Type III (2HDM-III) and assess the LHeC sensitivity to such $H^-$ signals against a variety of both reducible and irreducible backgrounds. We confirm that prospects for $H^-$ detection in the 2HDM-III are excellent assuming standard collider energy and luminosity conditions.

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I. INTRODUCTION

Now that a neutral Higgs boson has been discovered at the Large Hadron Collider (LHC) by the ATLAS [1] and CMS [2] experiments, the SM appears to be fully established. However, the SM-like limit of Electro-Weak Symmetry Breaking (EWSB) dynamics induced by a Higgs potential exists in several Beyond the SM (BSM) extensions of the Higgs sector. Notably, the 2-Higgs Doublet Model (2HDM) in its versions Type I, II, III (or Y) and IV (or X), wherein Flavor Changing Neutral Currents (FCNCs) mediated by (pseudo) scalars can be eliminated under discrete symmetries [3], is an intriguing BSM candidate, owing to the fact that it implements the same fundamental doublet construct of the SM (albeit twice), assumes the same SM gauge group and predicts a variety of new Higgs boson states that may be accessible at the LHC. In fact, another, very interesting kind of 2HDM is the one where FCNCs can be controlled by a particular texture in the Yukawa matrices [4]. In particular, in previous papers, we have implemented a four-zero-texture in a scenario which we have called 2HDM Type III (2HDM-III) [5]. This model has a phenomenology which is very rich, which we studied at colliders in various instances [6]–[12], and some very interesting aspects, like flavor-violating quarks decays, which can be enhanced for neutral Higgs bosons with intermediate mass (i.e., below the top quark mass) [8]. Furthermore, in this model, the parameter space can avoid the current experimental constraints from flavor and Higgs physics and a light charged Higgs boson is allowed [11], so that the decay \( H^- \rightarrow b\bar{c} \) is enhanced and its Branching Ratio \( (BR) \) can be dominant. In fact, this channel has been also studied in a variety of Multi-Higgs Doublet Models (MHDMs) [13, 14], wherein the \( BR(H^- \rightarrow b\bar{c}) \approx 0.7 \rightarrow 0.8 \) and could afford one with a considerable gain in sensitivity to the presence of a \( H^- \) by tagging the \( b \) quark.

In this work, we tension the \( H^- \rightarrow b\bar{c} \) channel against the \( H^- \rightarrow \tau\bar{\nu}_\tau \) one and contrast the scope of the two modes in order to establish the sensitivity of the Large Hadron electron Collider (LHeC) [15] to the presence of light charged Higgs bosons of the 2HDM-III. Specifically, we study the process \( e^-p \rightarrow \nu_e H^-q \) (Fig. 1), where \( q \) represents both a light flavor \( q = d, u, s, c \) and a \( b \)-quark, followed by the decays \( H^- \rightarrow b\bar{c} \) and \( \tau\bar{\nu}_\tau \) (assuming in turn a leptonic decay of the \( \tau \) into an electron or muon). In the former case, we compare the signal yield against that of the main following background: \( \nu_3j, \nu_2bj, \nu_2j\bar{b} \) and \( \nu_{tb} \). In the latter case, we consider instead the backgrounds \( \nu j\ell\nu \) and \( \nu b\ell\nu \). (All relevant backgrounds are schematically represented in Figs. 2–3.)

The plan of this paper is as follows. In the next section we describe the 2HDM-III. Then we discuss our results. Finally, we conclude.

\[ \begin{array}{c}
\text{A)} \quad e^- \\
\text{B)} \quad \nu_e \\
\text{C)} \quad \nu_e \\
\end{array} \]

\[ \begin{array}{c}
\text{q}(b) \\
\text{q}(b) \\
\phi_0 \end{array} \]

\[ \begin{array}{c}
\text{H}^- \\
\text{W}^- \\
\phi_0^0 \end{array} \]

\[ \begin{array}{c}
\text{q}(b) \\
\text{q}(b) \\
\tilde{q}(t) \end{array} \]

\[ \begin{array}{c}
\text{H}^- \\
\text{W}^- \\
\phi_0^0 \end{array} \]

\[ \begin{array}{c}
\text{q}(b) \\
\text{q}(b) \\
\text{H}^- \\
\end{array} \]

FIG. 1. Feynman diagrams for the \( e^- p \rightarrow \nu_e H^-q \) process. Here, \( \phi_0^0 = h, H, A \), i.e., any of the neutral Higgs bosons of the BSM scenario considered here (see below).

II. 2HDM-III

In the 2HDM-III, the two Higgs (pseudo)scalar doublets, \( \Phi_1 \) and \( \Phi_2 \), have hypercharge +1 and both couple to all fermions. Here, a specific four-zero-texture is implemented as an effective flavor symmetry in the Yukawa sector, which we have shown previously being the mechanism controlling FCNCs. Therefore, it is not necessary to consider discrete symmetries in the Higgs potential [10, 11]. Then, one can study the most general
SU(2)_L \times U(1)_Y \text{ invariant (pseudo)scalar potential given by:}

\begin{equation}
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 + h.c.) \right) \\
+ \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_1^\dagger \Phi_1) \\
+ \left(\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + h.c. \right),
\end{equation}

where we assume all parameters to be real\footnote{The \(\mu_{12}^2, \lambda_5, \lambda_6 \text{ and } \lambda_7 \text{ parameters could be complex in general.}} including the Vacuum Expectation Values (VEVs) of the Higgs fields, hence there is no CP-Violating (CPV) dynamics. Usually, when a discrete symmetry \(\Phi_1 \rightarrow \Phi_1 \text{ and } \Phi_2 \rightarrow -\Phi_2\) is considered, the \(\lambda_6 \text{ and } \lambda_7\) parameters are absent. However, when mass matrices with a four-zero-texture are considered instead, one can keep the terms proportional to \(\lambda_6 \text{ and } \lambda_7\). Besides, we have shown that these parameters play a relevant role in one-loop processes, because self-interactions of Higgs bosons are sizable\footnote{In contrast, the EW parameter \(\rho\) receives large one-loop corrections directly by the mass difference between charged Higgs and CP-even/odd masses, which can be large irrespective of the value of \(\lambda_6 \text{ and } \lambda_7\).}. In contrast, the EW parameter \(\rho\) receives large one-loop corrections directly by the mass difference between charged Higgs and CP-even/odd masses, which can be large irrespective of the value of \(\lambda_6 \text{ and } \lambda_7\).
In general, for two (complex) doublet fields, there are eight fields but only five of them are physical (pseudo)scalar ("Higgs") fields, which correspond to: two neutral CP-even bosons \( h \) (the light one) and \( H \) (the heavy one), 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. In total, the 2HDM can be described by the parameters \( \alpha, \beta \) (where \( \tan \beta \) is the ratio of the VEVs of the two doublet fields) and the masses of the five Higgs particles. With these inputs one can estimate all the parameters that are present in the scalar potential.

In our construction, the Yukawa Lagrangian is given by [11]:

\[
\mathcal{L}_Y = - \left( Y_1^{u} \bar{Q}_L \phi_1 u_R + Y_2^{u} \bar{Q}_L \phi_2 u_R + Y_1^{d} \bar{Q}_L \phi_1 d_R + Y_2^{d} \bar{Q}_L \phi_2 d_R + Y_1^{l} \bar{L}_L \phi_1 l_R + Y_2^{l} \bar{L}_L \phi_2 l_R \right),
\]

where \( \phi_{1,2} = i \sigma_2 \phi_{1,2}^* \). So, the fermion mass matrices after EWSB are given by: \( M_f = \frac{1}{\sqrt{2}} \left( v_1 Y_1^f + v_2 Y_2^f \right) \), \( f = u, d, l \), where we have assumed that both Yukawa matrices \( Y_1^f \) and \( Y_2^f \) have the aforementioned four-zero-texture form and are Hermitian. After diagonalization, \( \tilde{M}_f = V_f^\dagger M_f V_f \), one has \( \tilde{M}_f = \frac{1}{\sqrt{2}} \left( v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f \right) \), where \( \tilde{Y}_i^f = V_f^\dagger Y_i^f V_f \).

One can obtain a good approximation for the product \( V_q Y_n^q V_q^\dagger \) by expressing the rotated matrix \( \tilde{Y}_n^q \) as [11]:

\[
[\tilde{Y}_n^q]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{\nu} [\chi_{n}^q]_{ij} = \frac{\sqrt{m_i^q m_j^q}}{\nu} [\chi_{n}^q]_{ij} e^{i \theta_{ij}^n},
\]

where the \( \chi \)s are unknown dimensionless parameters of the model. Following the procedure of [11], we can get a generic expression for the couplings of the charged Higgs bosons to the fermions as:

\[
\mathcal{L}_{\tilde{f},j,\phi} = - \left\{ \frac{\sqrt{\tau}}{\nu} \tilde{u}_i (m_d, X_{ij}, Y_{ij}) P_R + m_n Y_{ij} P_L \right\} d_j H^+ + \frac{\sqrt{\tau} m_i}{\nu} Z_{ij} \tilde{u}_j l R H^+ + h.c. \right\},
\]

where \( X_{ij}, Y_{ij} \) and \( Z_{ij} \) are defined as follows:

\[
X_{ij} = \sum_{i=1}^{3} (V_{\text{CKM}})_{il} \left[ X \frac{m_d}{m_{d_i}} \delta_{ij} - \frac{f(X)}{\sqrt{2}} \sqrt{\frac{m_d}{m_{d_i}}} \chi_{ij}^u \right],
\]

\[
Y_{ij} = \sum_{i=1}^{3} \left[ Y \delta_{il} - \frac{f(Y)}{\sqrt{2}} \sqrt{\frac{m_u}{m_{u_i}}} \chi_{ij}^u \right] (V_{\text{CKM}})_{lj},
\]

\[
Z_{ij} = \left[ Z \frac{m_l}{m_{l_i}} \delta_{ij} - \frac{f(Z)}{\sqrt{2}} \sqrt{\frac{m_l}{m_{l_i}}} \chi_{ij}^u \right],
\]

where \( f(a) = \sqrt{1 + a^2} \) and the parameters \( X, Y \) and \( Z \) are arbitrary complex numbers, which can be related to \( \tan \beta \) or \( \cot \beta \) when \( \chi_{ij}^f = 0 \) [11], thus recovering the standard four types of the 2HDM (see the Tab. 21), and the Higgs-fermion-fermion (\( \phi f f \)) couplings in the 2HDM-III are written as \( g_{2\text{HDM-III}}^{\phi f f} = g_{2\text{HDM-\text{any}}}^{\phi f f} + \Delta g \), where \( g_{2\text{HDM-\text{any}}}^{\phi f f} \) is the coupling \( \phi f f \) in any of the 2HDMs with discrete symmetry and \( \Delta g \) is the contribution of the four-zero-texture. Finally, we have also pointed out that this Lagrangian can represent a Multi-Higgs Doublet Model (M2HDM) or an Aligned 2HDM (A2HDM) with additional flavor physics in the Yukawa matrices [10, 11].

| 2HDM-III | X     | Y     | Z     |
|----------|-------|-------|-------|
| 2HDM Type I | \(- \cot \beta\) | \(\cot \beta\) | \(- \cot \beta\) |
| 2HDM Type II | \(\tan \beta\) | \(\cot \beta\) | \(\tan \beta\) |
| 2HDM Type X | \(- \cot \beta\) | \(\cot \beta\) | \(\tan \beta\) |
| 2HDM Type Y | \(\tan \beta\) | \(\cot \beta\) | \(- \cot \beta\) |

TABLE I. The parameters \( X, Y \) and \( Z \) of the 2HDM-III defined in the Yukawa interactions when \( \chi_{ij}^f = 0 \) so as to recover the standard four types of 2HDM.

2 So that we will refer to these 2HDM-III ‘incarnations’ as 2HDM-III like-\( \chi \) scenarios, where \( \chi = I, II, X \) and \( Y \) (to be defined below).
FIG. 4. Event rates $\sigma_{BR,L}$ at the LHeC with $\sqrt{s_{ep}} \approx 1.3$ TeV, where $\sigma \equiv \sigma(ep \rightarrow \nu_{e}H^{-}q)$ with $q = q_t$ or $b$ is the production cross section, $L = 100$ fb$^{-1}$ is the integrated luminosity and $BR$ is the decay fraction for the channel $H^{-} \rightarrow b\bar{c}$, for the following 2HDM-III scenarios: like-I (left), like-II (centre) and like-Y (right).

## III. BENCHMARK SCENARIOS

The 2HDM-III has been constrained previously by us, see Refs. [8–12], by taking into account both flavor and Higgs physics as well as EW Precision Observables (EWPOs) (e.g., the oblique parameters) plus theoretical bounds such as vacuum stability, unitarity as well as perturbativity. In particular, the parameter space of the 2HDM-III with a four-zero-texture considered here is fully compatible with the SM-like Higgs boson discovery [9–11]. We consider four scenarios, wherein relevant Benchmarks Points (BPs) are defined according to the standard Yukawa prescriptions:

- Type I (where one Higgs doublet couples to all fermions); Type II (where one Higgs doublet couples to the up-type quarks and the other to the down-type quarks); Type X (also called IV or "Lepton-specific", where the quark couplings are Type I and the lepton ones are Type II); Type Y (also called III or "Flipped" model, where the quark couplings are Type II and the lepton ones are Type I).

For a light charged Higgs boson, in the 2HDM-III, the most important decay channels are $H^{-} \rightarrow s\bar{c}$ and $b\bar{c}$, when $Y \gg X, Z$ (like-I scenario), $X, Z \gg Y$ (like-II scenario) or $X \gg Y, Z$ (like-Y scenario), in which cases the mode $H^{-} \rightarrow b\bar{c}$ receives a substantial enhancement, coming from the four-zero-texture implemented in the Yukawa matrices, so as to obtain even a $BR(H^{-} \rightarrow b\bar{c}) \approx 0.95$, so that we focus on this decay, also owing to the fact that it can be $b$-tagged, thus reducing in turn the level of background. However, for the case $Z \gg X, Y$ (like-X scenario), the decay channel $H^{-} \rightarrow \tau\nu_{\tau}$ is maximized, reaching a $BR$ of 90% or so [11], so that we will investigate this mode as well.

In this work, considering the parameter scan performed in [8], we adopt the following BPs, where the aforementioned two decay channels ($H^{-} \rightarrow b\bar{c}$ and $H^{-} \rightarrow \tau\nu_{\tau}$) offer the most optimistic chances for detection.

- Scenario 2HDM-III like-I: $\cos(\beta - \alpha) = 0.5$, $\chi_{u}^{22} = 1$, $\chi_{23}^{2} = 0.1$, $\chi_{33}^{u} = 1.4$, $\chi_{22}^{d} = 1.8$, $\chi_{23}^{d} = 0.1$, $\chi_{33}^{d} = 1.2$, $\chi_{22}^{1} = 1$, $\chi_{22}^{2} = -0.4$, $\chi_{23}^{2} = 0.1$, $\chi_{33}^{2} = 1$ with $Y \gg X, Z$.
- Scenario 2HDM-III like-II: $\cos(\beta - \alpha) = 0.1$, $\chi_{u}^{22} = 1$, $\chi_{23}^{u} = -0.53$, $\chi_{33}^{u} = 1.4$, $\chi_{22}^{d} = 1.8$, $\chi_{23}^{d} = 0.2$, $\chi_{33}^{d} = 1.3$, $\chi_{22}^{1} = 1$, $\chi_{22}^{2} = -0.4$, $\chi_{23}^{2} = 0.1$, $\chi_{33}^{2} = 1$ with $X, Z \gg Y$.
- Scenario 2HDM-III like-X: the same parameters of scenario 2HDM-III like-II but $Z \gg X, Y$.
- Scenario 2HDM-III like-Y: the same parameters of scenario 2HDM-III like-II but $Z \gg Y, Z$.

For all four benchmarks scenarios, we assume $m_h = 125$ GeV and consider $m_A = 100$ GeV, 130 GeV < $m_H < 250$ GeV and 100 GeV < $m_{H^\pm}$ < 170 GeV.

Before proceeding to investigate the aforementioned two $H^{-}$ decays, in order to gain some insights into the inclusive event rates available, we show in Figs. [I] and [II] a scan over the relevant parameters $X, Y$ and $Z$ for the four 2HDM-III incarnations, each in correspondence of the relevant $H^{-} \rightarrow b\bar{c}$ and $H^{-} \rightarrow \tau\nu_{\tau}$ decay channels, respectively. Assuming the LHeC standard Centre-of-Mass (CM) energy of $\sqrt{s_{ep}} \approx 1.3$ TeV and luminosity of $L = 100$ fb$^{-1}$, it is clear that inclusive event rates are substantial, of order up to several thousands in all four cases, so that the potential of the LHeC in extracting the $H^{-} \rightarrow b\bar{c}$ and $H^{-} \rightarrow \tau\nu_{\tau}$ decays is definitely worth exploring further. In fact, the main objective of our analysis is to tension one decay against the other and extract the corresponding significances, which may lead to evidencing or indeed discovering the true underlying 2HDM structure onsetting EWSB.
FIG. 5. Event rates $\sigma_{BR.L}$ at the LHeC with $\sqrt{s_{ep}} \approx 1.3$ TeV, where $\sigma \equiv \sigma(ep \rightarrow \nu_e H^- q)$ with $q = q_l$ or $b$ is the production cross section, $L = 100$ fb$^{-1}$ is the integrated luminosity and BR is the decay fraction for the channel $H^- \rightarrow \tau\bar{\nu}_\tau$, for the following 2HDM-III scenario: like-X.

IV. DISCUSSION

As intimated, in the framework of the 2HDM-III considered here, there are two main $H^\pm$ decay channels, which are $H^- \rightarrow b\bar{c}$ (the leading one for the incarnations like-I, -II and -Y) and $H^- \rightarrow \tau\bar{\nu}_\tau$ (the leading one for the incarnation like-X). Some BPs, maximising the signal rates in the four 2HDM-III incarnations defined in terms of the parameters $\chi_{ij}^f$ and $X, Y$ and $Z$ introduced previously, are given in Tab. II, wherein the relevant BRs of the $H^\pm$ state are given alongside the cross sections of the associated production process $ep \rightarrow \nu_e H^- q$, where $q = q_l$ or $b$. (However, we have eventually verified that only the case $q = b$ is phenomenologically relevant, so that, henceforth, we neglect discussing the case $q = q_l$ explicitly, though it is included in our simulations.)

The signatures that we will consider are as follows.

- On the one hand, in connection with the 2HDM-III like-I, -II and -Y, wherein the most relevant decay process is $H^- \rightarrow b\bar{c}$, the final state is $3j + E_T$ (where $j$ is a generic jet and $E_T$ refers to missing transverse energy), with one $b$-tagged and one light jet (associated to the charged Higgs boson reconstruction) accompanied by a remaining jet which can be $b$-tagged or not.

- On the other hand, in connection with the 2HDM-III like-X, wherein the most relevant decay process is $H^- \rightarrow \tau\bar{\nu}_\tau$, the final state is $j + l + E_T$, where $l = e, \mu$ (from a leptonic $\tau$ decay) and the jet is $b$-tagged.

In this upcoming discussion we will describe the phenomenology of these two possible processes. In order to carry out our numerical analysis, we have used CalcHEP 3.7 [16] as parton level event generator, interfaced to the CTEQ6L1 Parton Distribution Functions (PDFs) [17], then PYTHIA6 [18] for the parton shower, hadronisation and hadron decays and PGS [19] as detector emulator, by using a LHC parameter card suitably modified for the LHeC. In particular, the detector parameters simulated were as follows: we considered a calorimeter coverage $|\eta| < 5.0$, with segmentatiton $\Delta\eta \times \Delta\phi = 0.0359 \times 0.0314$ (the number of division in $\eta$ and $\phi$ are 320 and 200, respectively). Moreover, we used Gaussian energy resolution, with

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

where $a = 0.003$ and $b = 0.085$ for Electro-Magnetic (EM) calorimeter resolution or $b = 0.32$ for hadronic calorimeter resolution. The algorithm to perform jet finding was a “cone” with jet radius $\Delta R = 0.5$. The calorimeter trigger cluster finding a seed(shoulder) threshold was 5 GeV (1 GeV). We took $E_T(j) > 10$ GeV for a jet to be considered so, in addition to the isolation criterion $\Delta R(j; l) > 0.5$. Finally, we have mapped the kinematic behavior of the final state particles using MadAnalysis5 [20].

A. The process $e^- q \rightarrow \nu_e H^- b$ with $H^- \rightarrow b\bar{c}$ for the 2HDM-III like-I, -II and -Y

In this subsection we discuss the final state with one $b$-tagged jet and one light jet (associated with the secondary decay $H^- \rightarrow b\bar{c}$) alongside a generic (i.e., light or $b$-tagged) forward jet (associated with the primary collision) plus
missing transverse energy. For this case, we apply the following cuts\(^3\).

I) First, we select only events with exactly three jets in the final state. Then, we reject all events without a b-tagged jet. Hence, at this point, we keep events like \(3j + E_T\) with at least one b-tagged jet (see the histograms in Fig. 6). For these selections, our signal generally has an efficiency of 12\% while the most efficient background \(\nu_c bbj\) has a 10\% response. The remaining backgrounds have efficiencies of 5\%, 8\% and 1\% for \(\nu_c bt\), \(\nu_c bjj\) and \(\nu_c jjj\), respectively.

II) The second set of cuts is focused on selecting two jets (one b-tagged, labelled as \(b_{\text{tag}}\), and one not, labelled as \(j_c\)) which are central in the detector. First, we demand that \(P_T(b_{\text{tag}}) > 30(40)\) GeV and \(P_T(j_c) > 20(30)\) GeV for \(m_{H^\pm} = 110, 130(150, 170)\) GeV (here, \(P_T\) is the transverse momentum). Then, we impose a cut on the pseudorapidity \(|\eta(b_{\text{tag}}, j_c)| < 2.5\) of both these jets and, finally, select events in which \(1.8(2) < \Delta R(j_c; b_{\text{tag}}) < 3.4(3.4)\) in correspondence of \(m_{H^\pm} = 110, 130(150, 170)\) GeV (where \(\Delta R\) is the standard cone separation). Upon enforcing these cuts, we find that our signal has a cumulative efficiency of 7.3\%. The most efficient background \(\nu_c bjj\) has a rate of 6\% while the others show efficiencies of 3.3\%, 3.7\% and 0.3\% (for \(\nu_c bt\), \(\nu_c bjj\) and \(\nu_c jjj\), respectively). This information is easily drawn from Fig. 6.

III) The next cut is related to the selection of a forward third generic jet (it can be either a light jet or a b-tagged one). Our selection for such a third jet is \(|\eta| > 0.6\) (with a transverse momentum above 20 GeV). With this cut, our signal shows an efficiency of 5.4\% while 4.2\% is the rate for the most efficient background (\(\nu_c bjj\)). The rest of the backgrounds show efficiencies below 2\% for \(\nu_c bbj\) and \(\nu_c bt\) or 0.3\% for \(\nu_c jjj\).

IV) The selection of the jet pair representing a \(H^\pm\) candidate is made by considering only events for which the invariant mass of the two central jets is in the vicinity of the (trial) mass of the charged Higgs boson. However, it must be considered that, at the detector level, the signal may see a mass shift due to the finite efficiency in selecting the wanted jet dynamics. Therefore, in the histograms of Fig. 6 we study such invariant mass in the case of our signal for, e.g., \(m_{H^\pm} = 110\) (left) and 130 (right) GeV. We benchmark these against the corresponding spectra from the backgrounds. From this plot, we can indeed see a shift of the signal peaks

\(^3\) For illustration, we assume the 2HDM-III like-Y scenario in our description, though the signal kinematics is essentially independent of the theoretical setup, as it primarily depends on the \(m_{H^\pm}\) value.
FIG. 7. Distributions for the process $e^- q \rightarrow \nu_e H^- b$ followed by $H^- \rightarrow b\bar{c}$: in the top-left panel we present the transverse momentum of the central $b$-tagged jet, in the top-right panel we present the transverse momentum of the central light jet, in the bottom-left panel we present the pseudorapidity of the central light jet while in the bottom-right panel we present the separation between the two central jets. The like-Y case is illustrated. The normalisation is to unity.

FIG. 8. Distributions for the process $e^- q \rightarrow \nu_e H^- b$ followed by $H^- \rightarrow b\bar{c}$ in the invariant mass of the two central jets for $m_{H^\pm} = 110$ GeV (left) and $m_{H^\pm} = 130$ GeV (right). The like-Y case is illustrated. The normalisation is to the total event rate for $L = 100$ fb$^{-1}$.

towards lower invariant masses, so that we can implement the following selection criterium: $m_{H^\pm} - 20$ GeV $< M(b_{\text{tag}}, j_{c}) < m_{H^\pm}$. Furthermore, we noticed that the invariant mass formed by the light central jet and the generic forward jet (not shown here) has a structure in most of the backgrounds, dictated by the presence of a hadronic $W^\pm$ boson decay. Because our signal does not have this feature, we further impose that $M(j_{c}, j_{f}) > 80$ GeV or $M(j_{c}, j_{f}) < 60$ GeV (where $j_{f}$ labels the forward jet). This combination of mass cuts is highly selective, giving us an overall efficiency of 2.4% for the signal and (at most) 0.6% for the backgrounds.

The final results, following the application of Cuts I–IV, are found in Tab. III for the 2HDM-III like-I, -II and -Y incarnations. Statistically, significances of the signal $S$ over the cumulative background $B$ are very good at low $H^\pm$ masses already for 100 fb$^{-1}$ of luminosity. As the latter increases, larger masses can be afforded through evidence or discovery, particularly so in the like-Y scenario. However, a ultimate mass reach is probably 130 GeV in all cases.

B. The process $e^- q \rightarrow \nu_e H^- b$ with $H^- \rightarrow \tau \bar{\nu}_\tau$ in the 2HDM-III like-X

Now we focus our attention on the channel $H^- \rightarrow \tau \bar{\nu}_\tau$. To this effect, as previously mentioned, we look at leptonic $\tau$ decays ($\tau \rightarrow l\bar{\nu}_l\nu_l$, with $l = e, \mu$) and we $b$-tag the prompt (i.e., coming from the primary collision) jet in the final state. The cuts to extract our signal are presented below.
I) This first set of cuts is focused on selecting events with one b-tagged jet and one lepton, by imposing $|\eta(b_{\text{tag}}, l)| < 2.5$, $P_T(b_{\text{tag}}, l) > 20$ GeV and the isolation condition $\Delta R(b_{\text{tag}}, l) > 0.5$ (see Fig. 9 for the histograms of the lepton and jet multiplicities.) Following this, we find that our signal has an efficiency of 14% whereas the backgrounds $\nu_e\nu_l j$ and $\nu_e\nu_l b$ have rates of 23% and 18%, respectively. The remaining noise shows an efficiency below 5%.

II) The next set of cuts enables us to select a stiffer lepton and impose conditions on the missing transverse energy which are adapted to the trial $H^\pm$ mass. We select events with $P_T(l) > 25(40)$ GeV and $E_T > 30(40)$ GeV for $m_{H^\pm} = 110, 130(150, 170)$ GeV. Our signal presents an efficiency of 70% while 80% is the rate for $\nu_e\nu_l j$, $\nu_e\nu_l b$ and $\nu_e b$.

III) Then, based on the left frame of Fig. 11, we require $|\eta(b_{\text{tag}})| > 0.5$. Furthermore, upon defining the total hadronic transverse energy $H_T = \sum_{\text{hadronic}} P_T$ in the final state, based on the right frame of Fig. 11, we select $H_T < 60$ GeV. For our signal, these cuts are little discriminatory and show an efficiency of 75%. However, for all backgrounds, the efficiency is in general below 50%.

IV) Finally, we enforce the last selection by exploiting the transverse mass $M_T(l)^2 = 2P_T(l)E_T(1 - \cos \phi)$, where $\phi$ is the relative azimuthal angle between $p_T(l)$ and $E_T$. A quantity which allows one to label the candidate events reconstructing the charged Higgs boson mass. However, the existence of one additional neutrino in the final state ($\nu_e$) emerging from the primary hard collision, alongside the two stemming from the $\tau$ decay ($\nu_\tau$ and $\nu_l$), generates a widening of the transverse mass distribution of the signal. Therefore, we make the following selection: $m_{H^\pm} - 50$ GeV $< M_T(l) < m_{H^\pm} + 10$ GeV (see Fig. 12). For this cut, our signal has a cumulative efficiency of 1%, quite comparable to the efficiency of $\nu_l b$, which is 0.9%. The rest of the backgrounds are instead below 0.2%

The effectiveness of this selection strategy is confirmed by the final results in Tab. IV, wherein we present the signal and background rates along with the corresponding significances after Cuts I–IV for the usual values of luminosity. Again, also in the like-X case, good sensitivity exists up to $H^\pm$ masses of 130 GeV.

V. CONCLUSIONS

In conclusion, we have assessed the potential of a possible future LHeC, obtained from crossing $e^-$ and $p$ beams in the CERN tunnel currently hosting the LHC and previously LEP. The foreseen beam energies are 60 GeV and 7
TeV, respectively. Such an environment is rather clean and, since it primarily relies on a charged $W^-$ current for the hard scattering, conducive to the production of a negatively charged Higgs boson, $H^-$. This state is typical of 2HDMs and it is notoriously elusive at the LHC [13, 21], so that it is natural to assess the scope for its detection at the LHeC. As 2HDM theoretical framework we have adopted a 2HDM-III supplemented by a four-zero-texture in the Yukawa sector which enables one, firstly, to avoid imposing a $Z_2$ symmetry to prevent FCNCs and, secondly, to re-create the standard 2HDM setups, known as Type I, II, X and Y, through suitable choices of the texture matrix elements. Such a scenario can realistically only afford one with LHeC sensitivity to rather light $H^\pm$ masses, i.e., well below the top mass. In this mass regime, though, we have established that the LHeC can access $H^\pm$ masses up to 130 GeV or so, for luminosity conditions already foreseen for such a machine. This assessment is essentially similar for all 2HDM-III incarnations, although sensitivity is primarily established in the like-I, -II and -Y cases via $H^- \rightarrow b\bar{c}$ and in the like-X case via $H^- \rightarrow \tau\bar{\nu}_\tau$ (assuming electron/muon decays of the $\tau$). The LHeC production mode is $e^- q \rightarrow \nu_e H^- q$, with $q = b$ being the dominant sub-channel, the latter being also induced by neutral Higgs boson exchange in $t$-channel (see Fig. 11). Hence, on the one hand, one can exploit the very efficient $b$-tagging expected at the LHeC detectors in order to establish the two signals above and beyond a variety of background channels, which we
FIG. 12. Distributions for the process $e^- q \rightarrow \nu_e H^- b$ followed by $H^- \rightarrow \tau \bar{\nu}_\tau$ in the transverse mass of the final state for $m_{H^\pm} = 110$ GeV (left) and $m_{H^\pm} = 130$ GeV (right). The like-X case is illustrated. The normalisation is to the total event rate for $L = 100$ fb$^{-1}$.

| Signal | Scenario | Events (raw) | Cut I | Cut II | Cut III | Cut IV | $(S/\sqrt{B})_{100 \, fb^{-1}}/(1000 \, fb^{-1}/3000 \, fb^{-1})$ |
|--------|----------|-------------|-------|--------|---------|--------|------------------------------------------------|
| $\nu_e H^- q$ | X-110 | 6480 | 178 | 124 | 94 | 67 | $2.41 \ (7.61) \ [13.19]$ |
| | X-130 | 3390 | 75 | 54 | 52 | 35 | $1.13 \ (3.58) \ [6.2]$ |
| | X-150 | 880 | 6 | 3 | 2 | 2 | $0.09 \ (0.29) \ [0.5]$ |
| | X-170 | 20 | 0.4 | 0.3 | 0.2 | 0.09 | $0.01 \ (0.02) \ [0.04]$ |
| $\nu_e bbj$ | | 20170 | 85 | 56 | 23 | 13 | |
| $\nu_e bjj$ | | 117559 | 623 | 340 | 122 | 84 | |
| $\nu_e tb$ | | 48845 | 460 | 374 | 149 | 105 | |
| $\nu_e jjj$ | | 867000 | 981 | 596 | 267 | 162 | |
| $\nu_e l\nu lj$ | | 23700 | 29 | 26 | 8 | 5 | $B = 763$ |
| $\nu_e l\nu lb$ | | 40400 | 1500 | 1203 | 569 | 392 | $\sqrt{B} = 27.62$ |

TABLE IV. Significances obtained after the sequential cuts described in the text for the signal process $e^- q \rightarrow \nu_e H^- b$ followed by $H^- \rightarrow \tau \bar{\nu}_\tau$ for four BPs in the 2HDM-III like-X. The simulation is done at detector level.

have done here, while, on the other hand, one could attempt extracting the $\phi_i^0 W^+ H^- (\phi_i^0 = h, H, A)$ vertex ‘directly’ in LHeC production (unlike the LHC, where it can only be done ‘indirectly’ in $H^-$ decays), which is what we shall do in a future publication.

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