Neutral and Charged Higgs boson phenomenology
at the LHeC and FCC-eh

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Abstract

We have analyzed the prospects of observing the lightest CP-even neutral Higgs boson \( h_1 \) via decays into \( b\bar{b} \) pairs in the neutral and charged current production processes \( e^- q \rightarrow e^- h_1 q \) and \( e^- q \rightarrow \nu_e h_1 q' \), respectively, at the planned Large Hadron electron Collider (LHeC), with an \( e^- \) beam energy of 60 GeV and a \( p \) beam energy of 7 TeV. We also focus on observing a relatively light charged Higgs boson \( h^- \) via its production mode \( e^- b \rightarrow \nu_e h^- b \) followed by the decays \( h^- \rightarrow s\bar{c} + s\bar{u} \) at the upcoming Future Circular Collider in hadron-electron mode (FCC-eh) with \( \sqrt{s} \approx 3.5 \) TeV. We have performed our analysis in the framework of the Next-to-Minimal Supersymmetric Standard Model (NMSSM) wherein the intermediate Higgs boson \( h_2 \) is Standard Model (SM)-like. We have considered constraints from Dark Matter (DM), superparticle and the Higgs boson data. In both analyses, we have carried out signal and background computations with selections optimized to the model at hand and found that in both cases it is possible to get large significances for low mass Higgs bosons.

1 Introduction

Since the discovery of a Higgs boson, with a mass of 125 GeV, at the Large Hadron Collider (LHC), by the ATLAS and CMS experiments, the SM with spontaneous Electro-Weak Symmetry Breaking (EWSB) is apparently well established. The SM contains one doublet of Higgs isospin.
Nonetheless, many models with enlarged Higgs sectors still survive LHC SM-like Higgs data. In fact, any deviations from SM predictions would be a hint in favor of new physics in Nature \cite{1}. Whereas several new physics scenarios exist that cannot only comply with the aforementioned LHC results (as well as explain other experimental observations that cannot be accounted for in the SM, such as neutrino and DM data) but also provide motivated theoretical frameworks (e.g., solving the hierarchy problem of the SM), it is fair to say that Supersymmetry (SUSY) is one of the most appealing ones.

However, it is very well known that SUSY in its minimal incarnation, called the MSSM, has several flaws. On the theoretical side, it suffers from the $\mu$-problem, as this parameter (effectively mixing the SUSY counterparts of Higgs states) ought to be below the TeV scale in order to enable successful EWSB, yet in the MSSM it can really naturally be only zero or close to the Planck mass. On the experimental side, its allowed parameter space is being more and more constrained from nil searches for new Higgs bosons or SUSY states. Both problems are remedied in the so called NMSSM \cite{2, 3}, wherein the Vacuum Expectation Value (VEV) of an additional Higgs singlet state can generate the $\mu$-term at the required scale and its SUSY counterpart can alleviate experimental bounds as it can act as a new DM state simultaneously altering SUSY cascade signals and the cosmological relic density. Just like in the MSSM, also the NMSSM has a pair of charged Higgs bosons ($h^\pm$) in its spectrum plus the possibility of a neutral CP-even Higgs boson lighter than the one discovered. In fact, a myriad of other non-minimal SUSY scenarios also have these states \cite{4}.

Non-standard neutral as well as charged Higgs bosons have been the focus of many analyses at the LHC. These searches are generally performed model-independently and then interpreted in specific scenarios, like the MSSM or NMSSM. Both Higgs states are normally searched for via flavor diagonal decays. More recently, the case for studying the (non-diagonal) flavor decay $h^- \rightarrow b\bar{c}$ has also vigorously been made in a variety of new physics scenarios thus encouraging the LHC experimental groups to look for this signal too \cite{5}.

At CERN, the future Large Hadron electron Collider (LHeC) and electron-proton Future Circular Collider (FCC-eh), with center-of-mass energies of 1.3 TeV and 3.5 TeV, respectively \cite{6, 7, 8}, offer good prospects as Higgs boson factories, wherein one could elucidate the nature of the couplings of Higgs bosons to fermions, especially the $b\bar{b}$ one, which is difficult to establish at the LHC, but also, e.g., of charged Higgs bosons to generic fermions. Given these encouraging prospects, we specifically analyze here the prospects of observing relatively light neutral and charged Higgs bosons of the NMSSM decaying via $b\bar{b}$ and $s\bar{c} + s\bar{u}$ modes, respectively.

## 2 NMSSM

We just mention here the relevant parts of the NMSSM. The superpotential is described as

$$W_{\text{Higgs}} = (\mu + \lambda \hat{S}) \hat{H}_u \cdot \hat{H}_d + \xi_F \hat{S} + \frac{1}{2} \mu' \hat{S}^2 + \frac{\kappa}{3} \hat{S}^3, \quad (1)$$

$$W_{\text{Yukawa}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + h_e \hat{H}_d \cdot \hat{L} \hat{E}_R^c, \quad (2)$$

$$W = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3. \quad (3)$$

The effective $\mu$-term is $\mu_{\text{eff}} = \lambda s$, where $s$ is the singlet VEV. Further, we invoke a simpler scenario in our analysis, namely, the $\mathbb{Z}_3$ symmetric version, wherein one can set $\mu = \mu' = \xi_F = 0$ and $m_S^2 = m_{\tilde{S}}^2 = \xi_S = 0$. In this model we have three neutral scalar fields and they mix to form
three mass eigenstates, generally describes as $h_1$, $h_2$ and $h_3$ (in increasing order of mass), where $h_2$ is considered as the SM-Higgs one in our analysis.

### 3 Numerical Analysis

Details of the tools used in our numerical analysis can be found in Refs. [9] and [10], including definition of the kinematic variables below.

#### 3.1 Neutral Higgs: $e^- p \rightarrow e^- h_1 q$ and $e^- p \rightarrow \nu_e h_1 q$ at the LHeC

Starting from the inclusive rates in Fig. 1 and after seeing various differential distributions (see details in [9]), we applied various selection cuts to isolate the Signal (S) from the Background (B) and performed some simple optimization to enhance the significances. In particular, we varied the following parameters over the ranges (min,max,step): $\eta_l(1.0,2.5,0.1)$, $\eta_l(-2.5,-1.0,0.1)$, $\Delta \eta_{j,l}(0.0,1.5,0.1)$, $\Delta \eta_{j,l}(-6.0,-3.0,0.1)$, $m_{\phi j}(80,180,10)$ GeV, $H_T^j(70,140,10)$ GeV and $|\bar{H}_T^j|(30,60,10)$ GeV. In Table 1 we show some Benchmark Points (BPs) and corresponding optimized significances. Signal extraction can be achievable at nearly 3\(\sigma\) with a low luminosity collider option while full discovery relies on higher data sample\(^7\).

#### 3.2 Charged Higgs: $eb(\bar{b}) \rightarrow eh^\pm b(\bar{b})$ at the FCC-eh

We show the Feynman diagram of these processes in the left-panel of Fig. 2. The inclusive event rate at FCC-eh energies is instead shown in the right-panel of Fig. 2. From the whole allowed parameter space, we selected three BPs where the number of signal events is substantial. Like in

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\(^7\)This mirrors the results of [11], albeit in another model.
Figure 2: Feynman diagram (left) and event rates (right) for $eb(b) \to eh^\pm b(b)$ at the FCC-eh.

Figure 3: Reconstructed di-jet (left) and final state (right) mass for $h^- \to s\bar{c} + s\bar{u}$.

the previous case, upon seeing various kinematical distributions, we initially applied a simple cuts and count method, which lead to small significances. To establish the mass of the charged Higgs boson, we show in the left-panel of Fig. 3 the di-jet invariant mass ($m_{jj}$). By combining together the charged Higgs boson candidate jets and a forward $b$-tagged jet, thus constructing the final state mass ($m_{jjb}$), some interesting features appear against the SM backgrounds (right panel of Fig. 3).

We thus performed again a multi-dimensional grid optimization as follows: $E_T(20.0, 40.0, 5)$ GeV, $H_T (95.0, 110.0, 5)$ GeV, $|\vec{H}_T|(20.0, 40.0, 5)$ GeV, $R_{M}(2.5, 3.5, 0.025)$, the upper value of $m_{jj}(m_{h^\pm}, m_{h^\pm}+10.0, 2.5)$ GeV, the lower value of $m_{jj}(m_{h^\pm}–25.0$ GeV, $m_{h^\pm}–15.0, 2.5$) GeV, the upper value of $\cos(\phi_{jj})(0.45, 0.55, 0.01)$ and the upper value of $\Delta R(\eta_{jj}, \phi_{jj})(2.1, 3.5, 0.1)$. For each of the generated combinations we estimated the number of S and B events plus the significances $S$. As shown in Table 2, there indeed exist combinations for which both evidence and (near) discovery of our $h^\pm$ signals can be established, albeit only at $1 \text{ ab}^{-1}$ of luminosity.
Table 2: S and B rates together with significances ($S$) for the $h^{-} \rightarrow s\bar{c} + s\bar{u}$ signals at the FCC-eh as function of the optimized cuts obtained for 100 fb$^{-1}$ (1 ab$^{-1}$).

| BP, $m_{h^{\pm}}$ (GeV) | $E_{T}$ | $H_{T}$ | $M_{jj}<M_{jj}>$ | $R_{M}$ | $\cos(\phi_{jj})$ | $\Delta R(\phi_{jj})$ | $S$ | $B$ | $S$ |
|--------------------------|---------|---------|----------------|--------|----------------|----------------|-----|-----|-----|
| BP1, 98.4                | 20.00   | 105.00  | 20.00          | 98.40  | 80.90          | 2.50   | 0.52 | 2.10 | 35.1 | 2.50 | 0.52 | 35.1 | 9053.5 | 0.37(1.18) |
|                          | 20.00   | 100.00  | 20.00          | 98.40  | 75.90          | 2.50   | 0.52 | 3.10 | 49.4 | 0.52 | 3.10 | 49.4 | 19714.8 | 0.35(1.12) |
|                          | 20.00   | 105.00  | 20.00          | 103.40 | 73.40          | 2.50   | 0.52 | 3.10 | 49.4 | 0.52 | 3.10 | 49.4 | 19714.8 | 0.35(1.12) |
| BP2, 114.6               | 20.00   | 110.00  | 20.00          | 114.60 | 99.50          | 2.50   | 0.45 | 2.10 | 74.7 | 0.45 | 2.10 | 74.7 | 5850.4 | 0.34(1.08) |
|                          | 20.00   | 110.00  | 20.00          | 114.60 | 97.10          | 2.50   | 0.45 | 2.10 | 74.7 | 0.45 | 2.10 | 74.7 | 5850.4 | 0.34(1.08) |
|                          | 30.00   | 110.00  | 30.00          | 114.60 | 97.10          | 2.50   | 0.45 | 2.10 | 74.7 | 0.45 | 2.10 | 74.7 | 5850.4 | 0.34(1.08) |
| BP3, 121.3               | 20.00   | 95.00   | 20.00          | 121.30 | 96.30          | 2.50   | 0.45 | 2.80 | 64.5 | 0.45 | 2.80 | 64.5 | 8327.2 | 0.67(2.16) |
|                          | 20.00   | 100.00  | 20.00          | 121.30 | 96.30          | 2.50   | 0.45 | 2.80 | 64.5 | 0.45 | 2.80 | 64.5 | 8327.2 | 0.67(2.16) |

4 Conclusions

In the NMSSM, a $h_1 \rightarrow bb$ signal (with $h_1$ lighter than the SM-like state seen at the LHC) can be discovered at the LHeC with up to approximately $3(8)\sigma$ significance for 100 fb$^{-1}$ (1 ab$^{-1}$) of luminosity. Further, at the FCC-eh with 100 fb$^{-1}$ (1 ab$^{-1}$) of integrated luminosity, charged Higgs signals $h^{-} \rightarrow s\bar{c} + s\bar{u}$ could achieve significances up to $\approx 4.4(2.2)\sigma$ for $m_{h^{\pm}} = 114(121)$ GeV.

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