Inverted neutrino mass hierarchy and new signals of a chromophobic charged Higgs at the Large Hadron Collider

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Abstract

We explore the signals of a charged Higgs arising in a two Higgs doublet model respecting \(SU(2)_L \times U(1) \times Z_2\) symmetry with three singlet right handed neutrinos, \(N_R\). The charged Higgs in this model has negligible coupling with quarks, and has unsuppressed coupling to leptons and neutrinos. This leads to novel signatures of the charged Higgs at the LHC, especially in the case of an inverted neutrino mass hierarchy, in the form of electrons and muons with missing energy.

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1 Introduction

Although the Higgs boson, the central pillar of the standard electroweak model (SM) is yet to be observed, there are speculations on the possibility of a Higgs sector extending beyond the single Higgs doublet scenario postulated in the SM. The motivations for such an extended Higgs sector, with masses of the additional scalars within an experimentally accessible range, are of different kinds, including the following:

- Supersymmetry, a widely studied theory for stabilizing the electroweak scale, which requires at least two Higgs doublets [1].

- Little Higgs theories [2], which seek to stabilize the electroweak scale by postulating a low-energy effective theory with several pseudo-goldstone bosons including the SM-type Higgs.

- Higgs bosons coming as part of a SU(2) triplet (either as consequences of a broken left-right symmetry or introduced in a purely phenomenological manner), which helps in the generation of neutrino masses in a type-II seesaw mechanism [3].

The above scenarios all imply the existence of charged scalar physical states, the experimental signals of which arise mostly through their coupling with heavy fermions such as the top and bottom quarks and the tau-lepton [4]. In some cases where the charged Higgs are ‘fermiophobic’, interactions with gauge bosons constitute the search channels [5]. However, light fermions like the electron and the muon are hardly considered relevant at the primary level, as far as the usually adopted search strategies for charged Higgs bosons are concerned. In this note, we suggest the signatures of charged Higgs in such an unusual channel at the Large Hadron Collider (LHC), as the consequence of a recently proposed model aimed at explaining the ultra-small neutrino masses.

The proposal is centred around two Higgs doublets, one of which ($\chi$) couples to all fermions excepting the neutrinos which are left out by virtue of a $Z_2$ symmetry. The other doublet ($\phi$) couples only with the charged leptons and the corresponding neutrinos which are Dirac fermions in this model [6]. A tiny vacuum expectation value (vev) of about $10^{-(1-2)}$ eV for $\phi$ is responsible for the smallness of the neutrino masses\footnote{Though this amounts to fine-tuning, the standard model itself, and most type-II seesaw models, are finely tuned to at least the same degree.}. The charged physical scalar...
which is constituted mostly out of $\phi$ couples to a charged lepton and a neutrino with large strength (proportional to the neutrino mass divided by a tiny vev of the order of the neutrino mass). Importantly, it is ‘chromophobic’ in nature, in the sense that it has no coupling with quarks.

The available data on neutrino masses and mixing admit three mass patterns, namely, normal hierarchy (NH), inverted hierarchy (IH) and degenerate neutrinos (DN) [7]. While the charged Higgs in this model interacts dominantly with $\tau \nu_3$ in the case of NH (where $m_3 >> m_2 \simeq m_1$), its dominant couplings in an IH scenario (with $m_2 \simeq m_1 >> m_3$) are with $\mu \nu_2$ and $e \nu_1$ in an equitable fashion. As a result, the charged Higgs scalar, produced, for example, through a Drell-Yan process at the LHC, will decay into muons and electrons (together with neutrinos) if one has IH in the neutrino mass patterns. Here we discuss the detectability of such novel charged Higgs signals. Due to the striking character of the signals, we mostly discuss the IH scenario, although we mention the NH case briefly.

We re-iterate the salient features of the model in section 2. Section three contains a discussion on the proposed signal, the strategies for eliminating backgrounds, and the predicted numerical results. We conclude in section 4.

## 2 The model and the formalism

Our proposed model [6] is based on the symmetry group $SU(3)_c \times SU(2)_L \times U(1) \times Z_2$. In addition to the usual SM fermions, we have three $SU(2)$ singlet right-handed neutrinos, $N_{Ri}$, $i = 1 - 3$, one for each family of fermions. The model has two Higgs doublets, $\chi$ and $\phi$. All the SM fermions and the Higgs doublet $\chi$, are even under the discrete symmetry, $Z_2$, while the RH neutrinos and the Higgs doublet $\phi$ are odd under $Z_2$. Thus all the SM fermions, except the left-handed neutrinos, couple only to $\chi$. The SM left-handed neutrinos, together with the right-handed neutrinos, couple only to the Higgs doublet $\phi$. The gauge symmetry $SU(2) \times U(1)$ is broken spontaneously at the electroweak scale by the vev of $\chi$, while the discrete symmetry $Z_2$ is broken by a vev of $\phi$, and we take $\langle \phi \rangle \sim 10^{-2} \text{ eV}$. Thus, in our model, the origin of the neutrino masses is due to the spontaneous breaking of the discrete symmetry $Z_2$. The neutrinos are massless in the limit of exact $Z_2$ symmetry. Through their Yukawa interactions with the Higgs field $\phi$, the neutrinos acquire masses much smaller than
those of the quarks and charged leptons due to the tiny vev of $\phi$.

The Yukawa interactions of the Higgs fields with the leptons are

$$L_Y = y_l \overline{\Psi}_L L_R \chi + y_\nu \overline{\Psi}_L N_R \tilde{\phi} + h.c., \quad (1)$$

where $\overline{\Psi}_L = (\overline{\nu}_l, \overline{l})_L$ is the usual lepton doublet and $l_R$ is the charged lepton singlet. The first term gives rise to the mass of the charged leptons, while the second term gives a tiny neutrino mass. The interactions with the quarks are the same as in the Standard Model with $\chi$ playing the role of the SM Higgs doublet. Note that in our model, a SM left-handed neutrino, $\nu_L$, combines with a right handed neutrino, $N_R$, to make a massive Dirac neutrino with a mass $\sim 10^{-2}$ eV, the scale of $Z_2$ symmetry breaking.

The most general Higgs potential consistent with the $SM \times Z_2$ symmetry is

$$V = -\mu_1^2 \chi^\dagger \chi - \mu_2^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2 + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 |\chi^\dagger \phi|^2 - \frac{1}{2} \lambda_5 [(\chi^\dagger \phi)^2 + (\phi^\dagger \chi)^2]. \quad (2)$$

The physical Higgs fields are a charged field $H$, two neutral scalar fields $h$ and $\sigma$, and a neutral pseudoscalar field $\rho$. In the unitary gauge, the two doublets can be written as

$$\chi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}(V_\phi/V_\chi)H^+ \\ h_0 + i(V_\phi/V_\chi)\rho + V_\chi \end{pmatrix},$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}(V_\chi/V_\phi)H^+ \\ \sigma_0 - i(V_\chi/V_\phi)\rho + V_\phi \end{pmatrix}, \quad (3)$$

where $V_\chi = \langle \chi \rangle$, $V_\phi = \langle \phi \rangle$, and $V^2 = V_\chi^2 + V_\phi^2$. The particle masses are

$$m_W^2 = \frac{1}{4}g^2 V^2, \quad m_{H^\pm}^2 = \frac{1}{2}(\lambda_4 + \lambda_5)V^2, \quad m_\rho^2 = \lambda_5 V^2,$$

$$m_{h,\sigma}^2 = (\lambda_1 V_\chi^2 + \lambda_2 V_\phi^2) \pm \sqrt{(\lambda_1 V_\chi^2 - \lambda_2 V_\phi^2)^2 + (\lambda_3 - \lambda_4 - \lambda_5)^2 V_\chi^2 V_\phi^2}. \quad (4)$$

An immediate consequence of the scenario under consideration is a very light scalar $\sigma$ with mass

$$m_\sigma^2 = 2\lambda_2 V_\phi^2[1 + O(V_\phi/V_\chi)]. \quad (5)$$
The mass eigenstates $h, \sigma$ are related to the weak eigenstates $h_0, \sigma_0$ by

$$h_0 = ch + s\sigma, \quad \sigma_0 = -sh + c\sigma,$$

where $c$ and $s$ denotes the cosine and sine of the mixing angles, and are given by

$$c = 1 + O(V_\phi^2/V_\chi^2),$$

$$s = -\frac{\lambda_3 - \lambda_4 - \lambda_5}{2\lambda_1}(V_\phi/V_\chi) + O(V_\phi^2/V_\chi^2).$$

Since $V_\phi \sim 10^{-2}$ eV and $V_\chi \sim 250$ GeV, this mixing is extremely small, and can be neglected. Hence, we see that $h$ behaves essentially like the SM Higgs (except of course in interactions with the neutrinos).

It is true that this model requires considerable fine-tuning, in order to maintain the hierarchy $\langle V_\phi \rangle/\langle V_\chi \rangle \sim 10^{-13}$, which is not naturally stable with respect to quantum corrections. However, this is no worse than the case in the usual non-supersymmetric grand unified theories, and also in the type II seesaw models for neutrino masses involving Higgs triplets. It will be interesting to see if the model can be supersymmetrized to resolve this. In any case, since the scenario suggested here has experimental signatures of a strikingly novel kind, we feel that its consequences are certainly worth exploring, much in the same way as the phenomenology of various other models have been explored in recent times.

From Eq.(3), we see that the charged Higgs mainly resides in the doublet $\phi$, with only a very tiny part, $V_\phi/V$ in $\chi$. Thus the coupling of the charged Higgs with the quarks are highly suppressed (hence the Chromophobic charged Higgs). However its coupling with the neutrinos and the corresponding charged leptons are not suppressed. Thus the charged Higgs will dominantly decay to the neutrinos and the charged leptons, giving a totally different signals from the usual generic two Higgs doublet models, or the MSSM. The Yukawa couplings of the charged Higgs, $H$ to the leptons and quarks are given by

$$L_Y = -\sqrt{2} \frac{m_\nu}{V_\phi} r_\chi [\bar{\nu}_L \nu_R H + \bar{\tau}_L \tau_R H + h.c.]$$

$$+ \sqrt{2} \frac{m_d}{V_\chi} r_\phi [\bar{u}_L d_R H - \sqrt{2} \frac{m_u}{V_\chi} r_\phi \bar{d}_L u_R H + h.c.]$$

where $r_\chi = V_\chi/V$ and $r_\phi = V_\phi/V$. The Feynman rules for the interaction of the charged Higgs with the photon, $Z$ boson and the scalars $\sigma$ and $\rho$ are given by
Fields & Couplings

|               | Couplings                                      |
|---------------|-----------------------------------------------|
| $A_\mu(p_1)$  | $H^+(p_2)$ $H^-(p_3)$                        |
| $Z_\mu(p_1)$  | $e(p_3 - p_2)^\mu$                           |
| $H^+(p_1)$    | $(1-2s_W^2)e$                                 |
| $\sigma(p_2)$ | $W^-(p_3)$                                    |
| $H^-(p_1)$    | $\rho(p_2) W^{+}(p_3)$                       |

The following important features of this model become apparent from the above description:

- The charged Higgs $H^\pm$ has practically no coupling to a pair of quarks (that is to say, these are ‘chromophobic’ scalars).

- While $h, \rho$ and $H^\pm$ have masses in the electroweak scale, $\sigma$ is an extremely light physical state whose mass is controlled by the vev $V_\phi$. $\sigma$ has interesting cosmological implications which was discussed in Ref. [6].

- The coupling of the charged scalar physical states $H^\pm$ to a lepton and the corresponding neutrino is large, proportional to the mass of the neutrino in that family divided by a tiny vev of the order of the corresponding neutrino mass.

- The main decays of $H^\pm$ are $H^\pm \rightarrow \ell\nu_\ell (\ell = e/\mu/\tau)$, $H^\pm \rightarrow \rho W^\pm$, and $H^\pm \rightarrow \sigma W^\pm$.

It is also to be noted that the absence of interaction with quarks makes the charged Higgs in this scenario free from all constraints arising from rare processes such as $b \rightarrow s \gamma$. Thus its mass can be anything above the limit from the search for pair-production at the Large Electron Positron (LEP) collider.

### 3 LHC signals for the charged Higgs

The chromophobic property of $H^\pm$ makes its search channels at the LHC quite different from the usual ones. The usual search strategies for charged Higgs at hadron colliders rely on its associated production with top quarks or from top quark decays. These production channels are denied in our case due to the chromophobic property of the charged Higgs. First of all, its production cannot take place through the process $bg \rightarrow tH^-$ [8] or through
top decays, \( t \to bH^+ \). One has to depend on electroweak processes leading to its pair-production. The pair productions of the charged Higgs in our model is via Drell-Yan process with the exchange of the photon and the Z boson in the s-channel. One could also have the charged Higgs boson pair produced at LHC through scattering of two electroweak gauge bosons via \( qq \to qqV^*V^* \to qqH^+H^- \) where \( V = \gamma, Z, W^\pm \) [9]. However we note that this cross section is suppressed compared to the Drell-Yan process. The production cross section for the charged Higgs pair through the Drell-Yan channel at the LHC energy are shown in Fig.1.

We can also produce the charged Higgs singly at LHC through the associated production channel \( qq' \to \rho H^\pm, \sigma H^\pm \). Both the production modes would lead to a single charged Higgs in the final state in association with large missing transverse energy as \( \rho \) decays to a pair of neutrinos with 100% branching ratio while \( \sigma \) passes through the detectors undetected [6]. For the single-\( H^\pm \) production channel, although the rates are of magnitude comparable to that of pair-production, the single-W background turns out to be overwhelmingly large, the

Figure 1: Cross section for the pair production of charged Higgs at LHC as a function of the charged Higgs mass. We have used the leading order parton density functions of CTEQ6L [10] for the analysis.
reason being the substantial branching ratio of the W to either an electron or a muon. Thus
the search for the charged Higgs in this scenario is best carried out via pair-production.

Decay branching ratios of the charged Higgs are determined by a competition between
the neutrino - charged lepton and the \( \sigma W \) and \( \rho W \) final states, the respective branching
ratios being decided by the vev \( V_\phi \) which in turn determines neutrino masses. Plots of the
branching ratios are shown in Fig. 2 where one finds that the fermionic decay modes are
more favoured for (a) low charged Higgs masses , and (b) relatively smaller values of \( V_\phi \).
The dominant fermionic decay mode is in the channel \( \tau \nu_\tau \) in the case of normal hierarchy of
neutrino masses. However, in the inverted hierarchy scenario the dominant fermionic decay
modes are to \( \mu \nu_\mu, e \nu_e \). Therefore, in case the IH scenario is preferred by nature, this model
predicts the rather striking signature for the charged Higgs, namely,

\[ p p \rightarrow H^+H^- \rightarrow \ell^+\ell^- + E_T \]
(with \( \ell, \ell' = e/\mu \)).

With the above final states in mind, we calculate the event rates for the signal and
compare them with the SM background. We have chosen a sample (benchmark) point in
the parameter space of the model for our analysis. The choice for the free parameters of the

Figure 2: We plot the branching ratio for the decay of charged Higgs boson as a function of
its mass. We also show, how the value of the vev for the second doublet affects the branching
ratios.
theory are

- $\lambda_1 = 0.12$, $\lambda_2 = 1.0$, $\lambda_3 = 2.0$
- $M_\rho = 100$ GeV, $M_\sigma \sim V_\phi = 10^{-2}$ eV and $M_h = 120$ GeV.
- $\lambda_5 = \frac{M_\rho^2}{V_\phi^2}$ and $\lambda_4 = \frac{2m_{H^+}^2}{V_\phi^2} - \lambda_5$.

It is worth pointing out that the charged Higgs production rate is not affected for other choices of the $\lambda_i's$ allowed by the model. However, as Fig.2 reveals, the choice of $V_\phi$ plays a crucial role in the decay properties of the charged Higgs. Also, the mass of the pseudoscalar $\rho$ influences the branching ratios for $m_{H^+} \lesssim m_W + M_\rho$ to some extent.

The SM background mainly comes from the process $pp \rightarrow W^+W^-$ and $pp \rightarrow ZZ$. In the first case the $W$-bosons decay to $e/\mu$ and a neutrino, while in the second, one of the $Z$ decays into neutrino and the other goes to an electron/muon pair. The second channel can be suppressed by removing the $Z$-peak in the invariant mass distribution of the charged lepton pair. In addition, a strong $E_T$ cut (which retains an appreciable fraction of the signal due to the larger mass of the charged Higgs) helps in reducing the SM background. It is important to note that, although the $W$-pair production cross section is quite large at LHC ($\sim 120$ pb) [11], the small branching ratio to $\ell\nu_\ell$ reduces the effective background rate as compared to the signal, for which the branching fraction is large when the $V_\phi$ is small (but approximately in the right range to yield proper neutrino masses with Yukawa couplings $O(1)$), and the charged Higgs mass is $\leq 300$ GeV.

However with additional jets coming from initial and final state radiations off the colliding partons, one expects the signal to be accompanied with jets. This leads to another major source for the SM background coming from the $t\bar{t}$ production. At first thought, this should be reducible by tagging the $b$-jets with large $E_T$ in the final state. Assuming an efficiency of 60% for a single $b$-jet identification, this should eliminate 84% of the background coming from the $t\bar{t}$ production. However, this does not prove sufficient to completely reduce this background. We note that this background can be effectively suppressed without losing much of the signal if we put a selection criterion on the maximum number of jets associated with the signal. Keeping this in mind we perform our analysis.

\footnote{We use the available NNLO corrected cross-section $\sim 890$ pb [12].}
Figure 3: We show the total cross section for the process $pp \rightarrow \ell^+ \ell^- + E_T$ as a function of the charged Higgs mass at the LHC, where $\ell = e, \mu$. The SM cross section is also shown in broken lines.

The SM background event generation has been done using PYTHIA 6.410 [13]. The signal events have been generated using the CalcHEP 2.4.5 [14] package and then interfaced with PYTHIA. To define the associated jets we employ the jet cone algorithm implemented in PYTHIA through the subroutine PYCELL. The minimum $E_T$ threshold for a cell to be considered as a jet initiator has been chosen as 2 GeV, while we assumed the minimum summed $E_T$ of the jet (consisting of all cells within the cone of radius $R$ in the $(\eta, \phi)$ plane) to be accepted as a jet to be 20 GeV. The jet conical width is $\Delta R_{jj} = \sqrt{\eta_{jj}^2 + \phi_{jj}^2} \geq 0.7$. While $\eta$ coverage range for jets is taken to be $|\eta| \leq 3.0$. Using the above clustering algorithm we find that if we restrict ourselves to $N_{jets} \leq 2$ (where $N_{jets}$ is the total number of jets) and using the $b$-jet identification efficiency, the background from the $t\bar{t}$ production is reduced to about $2 - 3 \ fb$ after implementing the selection cuts listed below. The dominant background still remains the one arising from the $W^+W^-$ production.

Based on the above observations and restricting ourselves to $N_{jets} \leq 2$, we have imposed the following cuts on our final state events:
• The transverse momentum of the charged lepton should respect a minimum cut $p_T^\ell > 25$ GeV.

• The charged leptons should be in the rapidity interval $|\eta^\ell| < 2.5$.

• A missing transverse energy(momentum) cut given by $E_T^{miss} > 100$ GeV.

• The $e/\mu$ should be well separated in space to be resolved, thus justifying $\Delta R_{\ell\ell} \geq 0.4$ where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.

• $M^{inv}_{\ell\ell} > 100$ GeV.

In Fig.3 we show a plot of the signal rate against the charged Higgs mass. The backgrounds are represented by the horizontal line. We see from Fig.3 that for $m_H < 150$ GeV, the signal to background ratio is greater than 1/3, while it falls to 1/6 for a 200 GeV charged Higgs. For $m_H \approx 300$ GeV this ratio falls to less than 1/30. It is clear from the figure that, although the background is sizable, such statistical significance as to set the signal apart can be achieved with sufficient integrated luminosity at the LHC. For an integrated luminosity of 10 $fb^{-1}$, one has a $5\sigma$ significance for $m_{H^\pm} \leq 140$ GeV while, if for example, one has $\int L dt = 100$ $fb^{-1}$ of luminosity, then one has a $\sim 5\sigma$ significance for $m_{H^\pm} \leq 220$ GeV. The search limit goes up to about 250 GeV with the same statistical significance for $\int L dt = 300$ $fb^{-1}$. Since the charged Higgs mass has little constraint on it other than that from Drell-Yan pair-production at the LEP, the above result is quite encouraging, as one is probing a substantial part of the parameter space of a chromophobic charged Higgs answering to an inverted hierarchy of neutrino masses.

We also present some kinematic plots of the signal in Fig.4 and Fig.5 and compare it with the SM background. The distributions show how the signal stands out better with larger $m_{H^\pm}$ so long as the production rate due to higher mass is not forbiddingly low.

In the case of a normal hierarchy of neutrino masses, the dominant coupling of $H^\pm$ is to a $\tau - \nu_\tau$ pair. The corresponding signal is $\tau^+\tau^- + E_T$, for which the rates without any cuts is same as that for the $e/\mu + E_T$ final state, since the branching ratio for $H^\pm \rightarrow \tau \nu_\tau$ in NH is the same as that for $H^\pm \rightarrow (e\nu_e + \mu\nu_\mu)$ in IH. The backgrounds, on the other hand, are reduced by a factor of four due to the smaller branching ratio of each W decaying into $\tau \nu_\tau$ only. Thus one expects prima facie a better search limit for the $H^\pm$ in this case.
Figure 4: We show the binwise distributions in the $\Delta R_{\ell^+\ell^-}$ and the invariant mass $M_{\ell^+\ell^-}$ for the $\ell^+\ell^- + E_T$ signal for three different choice of mass of the charged Higgs. The SM expectation is also shown in the shaded region. The vertical blue bands over the SM distribution represent the 3σ statistical fluctuations in the SM background. The integrated luminosity is taken as $\mathcal{L} = 100 \text{ fb}^{-1}$.

However, one has to study the effects of $\tau$-decays and the cuts on the decay products more carefully. An available option is to identify $\tau$-polarisation and thus separate the signals from the W-backgrounds, for which the polarisation is of opposite type. A detailed quantitative study of this signal pertaining to the NH case will be reported in a subsequent paper [15].

4 Conclusions

In a model motivated to explain the tiny neutrino masses, we have discussed a scenario in which the charged Higgs productions and decays are completely different from the usual two Higgs doublet models or MSSM. In this model, the dominant charged Higgs pair productions are via the Drell-Yan processes, where its decays are dominantly to the charged leptons and the corresponding neutrinos. In the inverted neutrino mass hierarchy scenario, the dominant decay modes are to the light leptons, electrons and muons. Such signals can be detected at the LHC for a charged Higgs mass upto few hundred GeV, and will provide a clue to the
Figure 5: We show the binwise distributions in the $p_T^l$ and the $E_T$ for the $\ell^+\ell^- + E_T$ signal for three different choice of mass of the charged Higgs. All conventions are the same as in Fig. 4. The integrated luminosity is taken as $\mathcal{L} = 100 \text{ fb}^{-1}$.

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