Production of charged Higgs $H^\pm$ through $cb$-fusion at LHC

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We consider the framework of the 2-Higgs Doublet Model Type III (2HDM-III), wherein two doublets are coupled to both up and down fermions and Flavour Changing Neutral Currents (FCNCs) are controlled by a four-zero texture approach in the Yukawa matrices. We study the production of charged Higgs bosons ($H^\pm$) by means of $cb$-quark fusion followed by the decay channel $H^\pm \rightarrow \tau^\pm \nu$. Taking into account all experimental bounds as well as theoretical constraints, we show that, in a lepton-specific-like incarnation of the model, we obtain a significant sensitivity to such a process at the Large Hadron Collider (LHC). We come to this conclusion after a thorough Monte Carlo (MC) analysis comparing the aforementioned signal to both irreducible and reducible backgrounds from the SM.

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I. INTRODUCTION

The Standard Model (SM) 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. The 2HDM [1] in its Types I, II, III (or Y) and IV (or X), wherein FCNCs mediated by (pseudo)scalar Higgs states can be eliminated under discrete symmetries [11], is one notable example. However, another, equally interesting 2HDM is the one where FCFNs can be controlled by a particular texture in the Yukawa matrices [2]. This model has a phenomenology that is very rich (see, e.g., Refs. [3–5]), like flavour-violating quarks decays. Furthermore, in this BSM scenario, the parameter space can avoid many of the current experimental constraints from flavour and Higgs physics, so that a light charged Higgs boson (i.e., with a mass below the top quark one) is allowed [10] and the decay $H^- \rightarrow b\bar{c}$ can have a dominant Branching Ratio (BR), much larger than those of the flavour diagonal $c\bar{c}$ and $t\bar{t}$ channels. (Notice that this channel has been studied in a variety of Multi-Higgs Doublet Models (MHDMS) [11,12], wherein the BR($H^- \rightarrow b\bar{c}$) $\approx$ 0.7–0.8 and one could obtain a considerable gain in sensitivity to the $H^\pm$ presence by tagging the $b$ (anti)quark. An experimental framework to search for this kind of signal has been investigated in [13].

In this work, by exploiting such an enhancement of the $H^- \rightarrow c\bar{b}$ vertex and building upon the results previously presented in Ref. [14], we study the production of a light charged Higgs state at the LHC via heavy-quark fusion $b\bar{c} \rightarrow H^-$ followed by the decay $H^- \rightarrow \tau\bar{\nu}_\tau$ (hereafter, charge conjugated channels are always implied), with the $\tau$ decaying leptonically. We investigate this process in the framework of the aforementioned 2HDM-III with so-called lepton-specific couplings and assess the LHC sensitivity to this production and decay dynamics against the irreducible background $qq' \rightarrow W^- \rightarrow \tau\bar{\nu}_\tau$ as well as the reducible noise due to $gg' \rightarrow W^\pm q$ (with an additional jet) and $q\bar{q} \rightarrow W^+W^- \rightarrow l^+l^-\nu\nu$ (where one lepton escapes detection).

II. THE 2HDM-III

As explained in [14] (and references therein), owing to the presence of a four-zero Yukawa texture as the mechanism to control FCNCs, the Yukawa sector of the 2HDM-III does not need a discrete symmetry [3–9]. Therefore, the Higgs potential for both doublets is given in the most general form,

$$V(\Phi_1, \Phi_2) = \mu_1^2(\Phi^\dagger_1 \Phi_1) + \mu_2^2(\Phi^\dagger_2 \Phi_2) - \mu_{12}(\Phi^\dagger_1 \Phi_2) + h.c.$$ \hspace{1cm} (1)

where the doublets $\Phi_i = (\phi^-, \phi^0_i) \ (i = 1, 2)$ have hypercharge +1 and all parameters of the Higgs potential are real, including the Vacuum Expectation Values (VEVs). In such a scenario, the Yukawa sector is given by

$$\mathcal{L}_Y = \left( Y_{1u}^u \bar{Q}_L \Phi_1 u_R + Y_{2u}^u \bar{Q}_L \Phi_2 u_R + Y_{1d}^d \bar{Q}_L \Phi_1 d_R + Y_{2d}^d \bar{Q}_L \Phi_2 d_R + Y_{1l}^e \bar{l}_L \Phi_1 \ell_R + Y_{2l}^e \bar{l}_L \Phi_2 \ell_R \right),$$ \hspace{1cm} (2)

where $\bar{\Phi}_i = i\sigma_2 \Phi_i^* \ (i = 1, 2)$ and the two doublets are coupled with both up and down type fermions. After EWSB and the diagonalisation of the fermion matrices we can obtain, as a good approximation, the rotated matrices $Y^f_\alpha$ by means of

$$Y^f_\alpha = \sqrt{\frac{m^f_i m^f_j}{v}} \chi^f_{ij},$$ \hspace{1cm} (3)

being the $\chi$'s parameters constrained by flavour physics, discussed widely in [8]. So, the interactions of charged Higgs bosons with fermions are given by

$$\mathcal{L}^{\bar{f}_\alpha} = -\left( \frac{\sqrt{2}}{v} \bar{u}_i(m_d X_{ij} P_R + m_u Y_{ij} P_L) d_j H^+ + \sqrt{2} \frac{\sqrt{2}}{v} m_{\ell} Z_{ij} \bar{\nu}_i \ell_R H^+ + h.c. \right),$$ \hspace{1cm} (4)

where $X_{ij}, Y_{ij}$ and $Z_{ij}$ are defined in [14], all being functions of the parameters $\chi$'s, in such a way that we can recover the usual models with discrete symmetry when the latter are absent. In general, the fermion-fermion-Higgs couplings $(\phi f f)$ in our model can be written as $g^{off}_{2HDM - III} = g^{off}_{2HDM - with - discrete - symmetry} + \Delta g$, being $\Delta g$ the contribution of the Yukawa texture.
III. NUMERICAL ANALYSIS

In this section, we present a brief report about some of the best Benchmark Points (BPs) available over the 2HDM-III parameter space in its lepton-specific incarnation. Full details about the numerical analysis can be found in [14]. In figure 1 we estimate the number of events $b\bar{c} \rightarrow H^+ \rightarrow \tau \nu$, with respect to the $Z$ and $Y$ parameters. The coloured regions represent parameter space that satisfies both theoretical and experimental constraints (for details, see [14]), specifically assuming $M_{H^\pm} = 120$ GeV. From these, we select one BP with $Y = 1.6$ and $Z = -20$ ($X = -1/Z = 0.04$), which produces around two million events at the LHC for current energy and luminosity. The main irreducible background comes from $q\bar{q} \rightarrow W^\pm \rightarrow \tau \nu$. However, the reducible backgrounds $gp \rightarrow W^\pm q$ and $q\bar{q} \rightarrow W^+W^-$ have to be considered too.

We then proceed to a full MC analysis, by using CalcHEP 3.7 [15] as an events generator, PYTHIA6 [16] for parton shower and PGS [17] as detector emulator (all details can be found [14]). Further, the final state particle kinematics was mapped with the help of MadAnalysis5 [18]. Because we look for leptonic $\tau$ decays, multiple neutrinos in the final state prevent us from reconstructing its invariant mass. Thus, we need to rely on the transverse mass to access the $H^\pm$ mass, so that figure 2 presents its shape for both signal and (total) background. In this plot, is possible to
see a Jacobian peak associated with the charged Higgs boson mass, to which it can be fit. However, the background produced a much larger number of events. Therefore, it is necessary to impose a set of cuts to extract our signal.

For the purpose of optimising our Signal \((S)\) versus background \((B)\) ratio, the first important condition to exploit is a jet veto in the final state. This initial cut reduces the background by half, while more than 60\% of the signal is preserved. For the rest of the events, we demand the following: \(p_T(l) > 45\text{ GeV}\), \(40\text{ GeV} < E_T < 70\text{ GeV}\), \(|\eta(l)| < 1.2\) and \(E_T > 55\text{ GeV}\). After imposing this set of cuts, the behaviour of the transverse mass is shown in figure 3. The final selection is over such a transverse mass. For the targeted \(H^\pm\) mass, we demand \(85\text{ GeV} < M_{T}(l) < 125\text{ GeV}\).

The numerical results after imposing the described cuts are found in table 1.

| Cut 1: \(p_T(k)\) | Cut 2: \(E_T\) | Cut 3: \(|\eta(l)|\) | Cut 4: \(E_T\) | Cut 5: \(M_T(l)\) |
|------------------|-------------|----------------|-------------|----------------|
| Signal           | 294136      | 237167         | 215684      | 85480          | 82147          |
| Background       | 27527568    | 7919086        | 3832807     | 1060294        | 795470         |

TABLE I. Number of events after imposing the cuts described in the text. The significance is \(S = S/\sqrt{S+B} = 87.68\). (From [14].)

FIG. 3. Transverse mass for signal and background after impose the cuts. (From [14].)

The numerical results after imposing the described cuts are found in table 1.

IV. CONCLUSIONS

To conclude, we believe it possible to extract a charged Higgs boson signal at the LHC within the 2HDM-III scenario in its lepton-specific incarnation, by searching for \(b\bar{c} \rightarrow H^- \rightarrow \tau \bar{\nu}_\tau\), with the \(\tau\) identified via decays into electrons/muons and corresponding neutrinos. If not already with present data for light charged Higgs bosons (as exemplified here), this could well happen by the end of Run 3 over a \(H^\pm\) mass interval ranging from 100 GeV or so up to the TeV scale, as seen in Ref. [14]. However, in order to achieve this, a dedicated selection procedure is required to be optimised around a tentative charged Higgs boson mass value, in order to suppress backgrounds effectively, both reducible and irreducible ones. We have obtained such results through a sophisticated MC analysis down to the detector level, so that we believe these to be solid enough to deserve further investigations by ATLAS and CMS.

[1] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, Phys. Rept. 516, 1 (2012) [arXiv:1106.0034 [hep-ph]].
[2] H. Fritzsch and Z. z. Xing, Phys. Lett. B 555, 63 (2003) [hep-ph/0212195].
[3] J. L. Díaz-Cruz, J. Hernández–Sánchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, Phys. Rev. D 79, 095025 (2009) [arXiv:0902.4490 [hep-ph]].
[4] J. Hernández-Sánchez, O. Flores-Sánchez, C. G. Honorato, S. Moretti and S. Rosado, PoS CHARGED 2016, 032 (2017) [arXiv:1612.06316 [hep-ph]].

[5] J. Hernández-Sánchez, S. P. Das, S. Moretti, A. Rosado and R. Xoxocotzi-Aguilar, PoS DIS 2015, 227 (2015) [arXiv:1509.05491 [hep-ph]].

[6] S. P. Das, J. Hernández-Sánchez, S. Moretti, A. Rosado and R. Xoxocotzi, Phys. Rev. D 94, no. 5, 055003 (2016) [arXiv:1503.01464 [hep-ph]].

[7] A. Cordero-Cid, J. Hernández-Sánchez, C. G. Honorato, S. Moretti, M. A. Pérez and A. Rosado, JHEP 1407, 057 (2014) [arXiv:1312.5614 [hep-ph]].

[8] O. Féliz-Beltrán, F. González-Canales, J. Hernández-Sánchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, Phys. Lett. B 742, 347 (2015) [arXiv:1311.5210 [hep-ph]].

[9] J. Hernández-Sánchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, PoS CHARGED 2012, 029 (2012) [arXiv:1302.0083 [hep-ph]].

[10] J. Hernández-Sánchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, JHEP 1307, 044 (2013) [arXiv:1212.6818 [hep-ph]].

[11] A. G. Akeroyd et al., Eur. Phys. J. C 77, no. 5, 276 (2017) [arXiv:1607.01320 [hep-ph]].

[12] A. G. Akeroyd, S. Moretti and J. Hernández-Sánchez, Phys. Rev. D 85, 115002 (2012) [arXiv:1203.5769 [hep-ph]].

[13] Slabospitsky, S. R., CMS-NOTE-2002-010 (2002) [arXiv:0203094[hep-ph]].

[14] J. Hernández-Sánchez, C. G. Honorato, S. Moretti and S. Rosado-Navarro, Phys. Rev. D 102, no.5, 055008 (2020) doi:10.1103/PhysRevD.102.055008 [arXiv:2003.06283 [hep-ph]].

[15] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. 184, 1729 (2013) [arXiv:1207.6082 [hep-ph]].

[16] T. Sjöstrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006) [hep-ph/0603175].

[17] J. Conway, R. Culbertson, R. Demina, B. Kilminster, M. Kruse, S. Mrenna, J. Nielsen, M. Roco, A. Pierce, J. Thaler and T. Wizansky, http://conway.physics.ucdavis.edu/research/software/pgs/pgs4-general.htm.

[18] E. Conte, B. Fuks and G. Serret, Comput. Phys. Commun. 184, 222 (2013) [arXiv:1206.1599 [hep-ph]].