New charged Higgs boson discovery channel at the LHC

R. Benbrik, M. Boukidi, B. Manaut, M. Ouchemhou, S. Semlali, and S. Taj

Polydisciplinary Faculty, Laboratory of Fundamental and Applied Physics, Cadi Ayyad University, Sidi Bouzid, B.P. 4162, Safi, Morocco.

Polydisciplinary Faculty, Laboratory of Research in Physics and Engineering Sciences, Team of Modern and Applied Physics, Sultan Moulay Slimane University, Beni Mellal 23000, Morocco.

School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom.

E-mail: r.benbrik@uca.ma, mohammed.boukidi@ced.uca.ma, b.manaut@usms.ma, ochemhou2@gmail.com, souad.semlali@soton.ac.uk, s.taj@usms.ma

Abstract: The ATLAS and CMS experiments have an ambitious search program for charged Higgs bosons. The two main searches for $H^\pm$ at the LHC have traditionally been performed in the $\tau\nu$ and $tb$ decay channels, as they provide the opportunity to probe complementary regions of the Minimal SuperSymmetric Model (MSSM) parameter space. Charged Higgs bosons may decay also to light quarks, $H^\pm \rightarrow cs/cb$, which represent an additional probe for the mass range below $m_t$. In this work, we focus on $H^\pm \rightarrow \mu\nu$ as an alternative channel in the context of two Higgs doublet model type III. We explored the prospect of looking $pp \rightarrow tbH^\pm$, followed by $H^\pm \rightarrow \mu\nu$ signal at the LHC. Such a scenario appears in 2HDM type-III where couplings of the charged Higgs are enhanced to $\mu\nu$. Almost all the experimental searches rely on the production and decay of the charged Higgs are taken into account. We show that for a such scenario, the above signal is dominant for most of the parameter space, and $H^\pm \rightarrow \mu\nu$ can be an excellent complementary search. Benchmarks points are proposed for further Monte Carlo analysis.
1 Introduction

The discovery of a Higgs boson by the ATLAS [1] and CMS [2] collaborations in 2012, which behaves very closely to the predictions of the Standard Model (SM), has played an extremely important role in the operation of the Large Hadron Colliders (LHC) so far. In the other hand, the search for physics beyond the Standard Model (BSM) have failed to yield any results, but there are interesting paths to investigate. Such Higgs boson was raised from $SU(2)_L$ doublet field boosting, a viable interpretation of the Higgs mechanism which lead to a spontaneous symmetry breaking of the electroweak symmetry. Several of these BSM theories argue for the presence of extra scalar particles. An eminent example is supersymmetry (SUSY). Introducing a new scalar boson for each SM fermion, resulting in a multiplicity of new particles. Extended models with simply a doublet scalar leads for example to general two Higgs Doublet Model (2HDM) [3, 4].

Clearly, the most general implementation of 2HDM has non-diagonal fermionic couplings in the flavour space, and can therefore induce flavor-changing neutral current (FCNC) effects at the tree level, which might be not consistent with the actual observations. The most basic alternative is to enforce a $Z_2$ symmetry, which prohibits unwanted non-diagonal terms. Following the $Z_2$ charge assignments to scalars and fermions, this leads to four realizations of 2HDMs type-I, -II,-X and -Y. The differences among these four settings is the manner in which the Higgs bosons couples to fermions are classified. Type-I is defined where one doublet couples to all fermions. Type-II is the situation where one doublet couples to up quarks and the other to down quarks and leptons. Type-X is the model where one...
doublet couples to all quarks and the other to all leptons, while a Type-Y is build such that one doublet couples to up quarks and leptons and the other to down quarks. An alternative solution is to also assume the so-called Cheng-Sher ansatz within the fermion sector, forcing the non-diagonal Yukawa couplings to become relative to the mass of the relevant fermions, which is called type III 2HDMs [5]. In this scenario, the avoidance of tree-level FCNC is guaranteed automatically by considering the alignment in the flavor space of Yukawa matrices. In the present study, the 2HDM type III will be thoroughly scrutinized. The diagonal matrix elements are fixed in order to be consistent with $B$-physics. By assuming CP conservation option, and very minimal version of Higgs couplings, the 2HDM comes with at least 7 free parameters; those are: Higgs masses, $m_h$, $m_H$, $m_{H^\pm}$, $m_A$; $\tan \beta = v_2/v_1$ which is the ratio of the vacuum expectation values of the two Higgs doublet fields; $\cos(\beta - \alpha)$ (or $\sin(\beta - \alpha)$) where $\alpha$ is the mixing angle of the CP-even Higgs states; and finally the $m_{12}^2$ free parameter.

A powerful approach to probe extended Higgs sectors is to search directly for new particles in collision experiments. In another way, extra Higgs bosons can be probed indirectly by precision measurements of the properties of the discovered Higgs boson, since the effects of extra Higgs bosons can be observed in the observable of the discovered Higgs boson by mixing Higgs states and/or loop corrections. A clean signature of non-minimal Higgs sectors is the existence of charged Higgs bosons, as they are expected in extended Higgs models with multiple Higgs doublet fields. The LHC has performed extensive searches for the charged Higgs boson at Run-1 and Run-2 in practically every possible channel by both experiments ATLAS [6–13] and CMS [14–17] with different luminosity running the mass range from 80GeV to TeV scale.

Both ATLAS [7] and CMS [15] experiments have set limits on $(m_{H^\pm}, \tan \beta)$ plane from $H^\pm \rightarrow \tau \nu$ observations at $\sqrt{s} = 8$ TeV and 13 TeV. Large $\tan \beta$ is excluded for light $m_{H^\pm}$. Moreover, intensive studies on light charged Higgs mass has been explored in 2HDM type-I, and type-X where the B physics constraints are weak. As at the LHC, the production cross-section $pp \rightarrow t\bar{t}$ followed by $t \rightarrow bH^+$ provides the main source of light charged Higgs boson for $\tau \nu$ channel together with $cs$ and $cb$. Low values of $\tan \beta < 2.3(1.4)$ are excluded for light charged Higgs mass up to top quark mass for type-III and type-I, respectively. The type-III 2HDM at intermediate $\tan \beta$ is one of the interesting discovery potential. In such scenario, the typical production of charged Higgs via the top channel becomes similar as type-I, but with very different behavior on charged Higgs branching ratio, resulting in spectacular signatures.

We have identified the potential importance of the $H^\pm$ bosonic decay model in various analyses. Associated charged Higgs production [19–26]. Alternatively, the electroweak production of $H^\pm$ [27–31] in partnership with a neutral (pseudo)scalar depends on gauge coupling and dominates over gauge coupling. For type-I 2HDM, the electroweak production of a charged light Higgs can result in a multi-photon or multi-boson final state [32–36].

The purpose of this paper is to explore $pp \rightarrow tbH^\pm, H^\pm \rightarrow \mu \nu$ in the current context of LHC, to assess the extent to which they might complement the searches for light charged Higgs. We will demonstrate that the production rates of such alternative production channel, in type-III, have the potential to be overwhelmingly stronger than the production
channels followed $H^\pm \rightarrow \tau \nu$. More specifically, we will illustrate that the leptonic decay of a lightly charged Higgs boson, could be dominant and give alternative reachable signatures to those arising from top quark production and decay. Consequently, such modes can serve as new discovery channels for light $H^\pm$ states at the LHC. We show that the proposed signal will discover or rule out a significant parameter space for Higgs scalars. The proposed signal complement the existing search strategies to expand the reach of LHC searches for charged Higgs.

The paper is organized as follows: In Sec. 2, we briefly discuss the type-III 2HDM model, including the Yukawa interaction. In Sec. 3 we discuss the existing theoretical and experimental bounds on the parameter space. Then we motivate towards $pp \rightarrow tbH^\pm, H^\pm \rightarrow \mu \nu$ signature in Sec. 4 where we also provide the details of the numerical analysis and we conclude in Sec. 5.

2 General 2HDM

The general 2HDM is one of the minimal extension of the SM Higgs sector, which consist of two doublet scalar fields $\Phi_i$ (i =1, 2) with hypercharge $Y = +1$. The most general 2HDM potential is given by [4]:

$$V_{Higgs}(\Phi_1, \Phi_2) = \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) +$$

$$+ \frac{1}{2} \left[ \lambda_5(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] + \left\{ \right. \left[ \lambda_6(\Phi_1^\dagger \Phi_1) + \lambda_7(\Phi_2^\dagger \Phi_2) \right] (\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\}$$

$$- \left\{ m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \right\}. \quad (2.1)$$

Following the hermiticity of Eq. (2.1), $m_{11}^2, m_{22}^2$ and $\lambda_{1,2,3,4}$ are real parameters, whereas $\lambda_{5,6,7}$ and $m_{12}^2$ can be complex. Assuming the CP conservation, $\lambda_5, m_{12}^2$ are real. In the models where $Z_2$ symmetry is extended to the Yukawa sector to suppress the flavors changing neutral currents (FCNC) at tree level, terms that are proportional to $\lambda_6$ and $\lambda_7$ in the scalar potential are absent. Note that in 2HDM Type-III with the off diagonal elements in Yukawa matrices[5, 37], $\lambda_7$ and $\lambda_6$ could be kept. In order to simplify the numerical analysis and to reduce the scanned parameters, it is more reasonable in this study to assume that in type-III, $\lambda_6 = \lambda_7 = 0$. After the electroweak symmetry breaking, we left with only 7 independent parameters: $m_{H^\pm}, m_A, m_H, m_h, \cos(\alpha - \beta), \tan \beta$ and $m_{12}^2$.

2.1 Yukawa interaction

We adopt the description presented in [5, 37] to keep the FCNC under control, while inducing flavor violating Higgs signals, by assuming a flavor symmetry that suggest a specific texture of the Yukawa matrices, where the non-diagonal Yukawa couplings, $\tilde{Y}_{ij}$, are given in terms of fermions masses and dimensionless real parameter, $\tilde{Y}_{ij} \propto \sqrt{m_i m_j / v} \chi_{ij}$. 

- 3 -
After the electroweak symmetry breaking (EWSB), we can rewrite the Yukawa Lagrangian in terms of physical scalar masses as:

\[ -\mathcal{L}^{	ext{Y}}_{\text{HI}} = \sum_{f=u,d,\ell} \frac{m_f}{v} \left[ (\xi_{ij}^f)_{ij} \bar{f}_L f_R j + (\xi_{ij}^f)_{ij} \bar{f}_L f_R j H - i (\xi_{ij}^f)_{ij} \bar{f}_L f_R j A \right] + \frac{\sqrt{2}}{v} \sum_{k=1}^{3} \tilde{u}_{ij} \left[ (m_i^u (\xi^u_A)_{kij} V_{kij} + V_{kij} (\xi^d_A)_{kij} m_j^d P_{Rj}) \right] d_j H^+ + \frac{\sqrt{2}}{v} \tilde{r}_{ij} (\xi^f_A)_{ij} m_j^f P_R \ell_j H^+ + \text{H.c.} \right. \]

In Table 1, we describe the Yukawa interactions in type-III in terms of the mixing angles and the free parameters \( \chi^f_{ij} \).

\[ \begin{array}{|c|c|c|c|}
\hline
\phi & (\xi^u_A)_{ij} & (\xi^d_A)_{ij} & (\xi^f_A)_{ij} \\
\hline
h & \frac{c_\alpha}{s_\beta} \delta_{ij} - \frac{c_\beta s_\alpha}{2s_\beta} \sqrt{m_i^u} \sqrt{m_j^d} \chi^u_{ij} & -\frac{c_\alpha}{s_\beta} \delta_{ij} + \frac{c_\beta s_\alpha}{2s_\beta} \sqrt{m_i^d} \sqrt{m_j^d} \chi^d_{ij} & -\frac{c_\alpha}{s_\beta} \delta_{ij} + \frac{c_\beta s_\alpha}{2s_\beta} \sqrt{m_i^f} \sqrt{m_j^f} \chi^f_{ij} \\
H & \frac{s_\alpha}{s_\beta} \delta_{ij} + \frac{s_\beta c_\alpha}{2s_\beta} \sqrt{m_i^u} \sqrt{m_j^d} \chi^u_{ij} & \frac{c_\alpha}{c_\beta} \delta_{ij} - \frac{s_\beta c_\alpha}{2s_\beta} \sqrt{m_i^d} \sqrt{m_j^d} \chi^d_{ij} & \frac{c_\alpha}{c_\beta} \delta_{ij} - \frac{s_\beta c_\alpha}{2s_\beta} \sqrt{m_i^f} \sqrt{m_j^f} \chi^f_{ij} \\
A & \frac{1}{t_\beta} \delta_{ij} - \frac{1}{\sqrt{2s_\beta}} \sqrt{m_i^u} \sqrt{m_j^d} \chi^u_{ij} & t_\beta \delta_{ij} - \frac{1}{\sqrt{2s_\beta}} \sqrt{m_i^d} \sqrt{m_j^d} \chi^d_{ij} & t_\beta \delta_{ij} - \frac{1}{\sqrt{2s_\beta}} \sqrt{m_i^f} \sqrt{m_j^f} \chi^f_{ij} \\
\hline
\end{array} \]

Table 1. Yukawa couplings of the \( h, H, \) and \( A \) bosons to the quarks and leptons in type-III 2HDM.

Note that the off diagonal terms of Yukawa matrices can be present, if \( i \neq j \). However, in our study, we will keep the version of 2HDM type-III without off diagonal terms in the Yukawa texture as shown in Eq 2.2 where \( \chi^f_{ij} = 0 \), for \( i \neq j \). The values of the on-diagonal elements in the Yukawa texture are as follows:

\[ \chi^u = \begin{pmatrix} 0.187 & 0 & 0 \\ 0 & 0.254 & 0 \\ 0 & 0 & 0.210 \end{pmatrix}, \quad \chi^d = \begin{pmatrix} -0.553 & 0 & 0 \\ 0 & 2.863 & 0 \\ 0 & 0 & 1.440 \end{pmatrix}, \quad \chi^f = \begin{pmatrix} 0.484 & 0 & 0 \\ 0 & -2.101 & 0 \\ 0 & 0 & 1.400 \end{pmatrix} \]

The free parameters \( \chi^u_{ij} \) are tested at the current constraints from B-physics observables by using SuperIso [49].

3 Theoretical and experimental bounds

In order to represent a viable BSM, the 2HDM has to respect certain theoretical and experimental constraints. The theoretical requirements included in 2HDM are perturbativity of the scalar quartic couplings, vacuum stability, and the tree-level perturbative unitarity conditions for various scattering amplitudes of gauge boson and Higgs state, these constraints reflect some important conditions in the space parameter of the model which will exhibit in the following:
• Unitarity constraints impose to a variety of scattering process to be unitary; scalar-
  scalar, gauge-boson–gauge boson, and scalar-gauge-boson, such conditions implies a
  set of inequality that have to be fulfilled on the eigenvalues of scattering matrix as
  follows $|e_i| < 8\pi$ [38–40]

• Perturbativity constraints impose to the quartic couplings of the scalar potential to
  obey the following conditions: $|\lambda_i| < 8\pi$ [4].

• Vacuum stability constraints require the potential to be bounded from below and
  positive in any direction of the field $\Phi_i$ , consequently, the space parameter must
  release the following condition [41, 42]:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$$

(3.1)

Besides the aforementioned theoretical constraints, we consider the experimental con-
straints comes from Electroweak Precision Observables (EWPOs), the null-searches
from LHC, LEP and Tevatron experiments, furthermore we requires agreement with
B-physics observable:

• Electroweak precision tests (EWPT): the agreement with electroweak precision ob-
  servables (EWPOs), parametrized through the electroweak oblique parameters $S$, $T$,
  $U$ at 95% C.L are required, their experimental limit are set as following [43–45].

$$S = 0.05 \pm 0.11, \quad T = 0.09 \pm 0.13, \quad U = 0.01 \pm 0.11.$$  

(3.2)

• Collider constraints: we ask for agreement with the limits obtained from various
  searches of additional Higgs bosons at the LHC as well as the requirement that one of
  the CP-even Higgs Boson should match the properties of the observed SM-like Higgs
  boson. We evaluate the former constraints with the tools HiggsBouns-5.9.0 [46, 47]
  and the latter with the tools HiggsSignal-2.6.0 [48].

• Flavour constraints: In our analysis we have used the B-physics observable cite on
  the Table.2, where we use the tools Superiso v4.1 [49] to calculate them.

The B physics observable that we have took are as following:

| Observable               | Experimental result | 95% C.L. Bounds                      |
|--------------------------|---------------------|-------------------------------------|
| $BR(B_{\mu} \to \tau\nu)$ | (1.06 ± 0.19) × 10^{-4} | [0.68 × 10^{-4}, 1.44 × 10^{-4}] |
| $BR(B_{s,d}^0 \to \mu^+\mu^-)$ | (2.8 ± 0.7) × 10^{-9} | [1.4 × 10^{-9}, 4.2 × 10^{-9}] |
| $BR(B_l^0 \to \mu^+\mu^-)$ | (3.9 ± 1.5) × 10^{-10} | [0.9 × 10^{-10}, 6.9 × 10^{-9}] |
| $BR(\bar{B} \to X_s\gamma)$ | (3.32 ± 0.15) × 10^{-4} | [3.02 × 10^{-4}, 3.61 × 10^{-4}] |

Table 2. Experimental results of flavor observables: $B_{\mu} \to \tau\nu$, $B_{s,d}^0 \to \mu^+\mu^-$ and $\bar{B} \to X_s\gamma$ at 95% C.L. Bounds.
3.1 Cross sections and branching ratios

We use the public tools 2HDMC-1.8[55] for checking the aforementioned theoretical constraint, the electroweak precision observables (EWPOs) as well as the different physical quantities pertinent to this phenomenological study.

We point out some of the recent constraints from searches for the charged Higgs boson. The ATLAS collaboration has set an upper limit between 0.25% and 0.031% for the branching fraction $B(t \to bH^\pm) \times B(H^\pm \to \tau^\pm \nu_\tau)$ in the range of masses varying from 90 GeV to 160 GeV after assuming the Standard Model cross-section for $t\bar{t}$ production [18]. An other search for charged Higgs boson in the same decay channel ($H^\pm \to \tau^\pm \nu_\tau$) for $H^\pm$ in the mass range of 80 GeV to 3 TeV is presented by ATLAS group [15]. In addition, the CMS collaboration has recently searched for a light charged Higgs boson with mass in the range 100 GeV to 160 GeV and a CP-odd Higgs boson with $15 \text{ GeV} < m_A < 75 \text{ GeV}$ in the decay chain, $t \to bH^\pm \to bW^\pm A \to bW^\pm \mu^+ \mu^-$, although, no significant excess is observed, upper limits are set on the product of branching fractions, $B(t \to bH^\pm) \times B(H^\pm \to W^+ A) \times B(A \to \mu^+ \mu^-)$ depending on $m_{H^\pm}$ and $m_A$ [56]. Furthermore, the ATLAS collaboration has also lately presented several searches for a heavier charged Higgs decaying into a top and bottom quarks, for $m_{H^\pm} > m_t + m_b$. No significant excess is reported and upper limits are set on $\sigma(H^\pm) \times B(H^\pm \to tb)$ as a function of $m_{H^\pm}$ [13, 57, 58].

3.2 B physics constraints

As a first check, on the B physics constraints using the public package SuperIso [49], we present in Figure 1, the relevant constraints related to flavor observables: $B_\mu \to \tau\nu$, $B_{s,d}^0 \to \mu^+ \mu^-$ and $B \to X_s \gamma$ which compatible the measurements at 95% C.L in both type-I(left) and type-III (right) panels. As for experimental limit we adopt LHCb collaboration [50, 51] and from PDG book [52]. The $B_{s,d}^0 \to \mu^+ \mu^-$ decay mode receive contributions from CP-odd Higgs boson proportional to $(\xi_A^2 m_A^4) / m_A^4$ [53]. As we can see, the possibility for light charged Higgs together with small $\tan \beta$ still compatible with recent measurements. From Fig 1 one can read that small values of $\tan \beta$ (< 1.3) are excluded by flavor physics constraints for different masses of $H^\pm$ in type-III, unlike type-I.

4 Numerical results

The extended scalar sector of CP-conserving 2HDM can allow two interesting possibilities which have been the subject of many studies, where one of the two CP-even Higgses can be identified as the observed 126 GeV state at the LHC, whose properties are approaching those of the SM. For comprehensive reviews, see [59, 60]. In the first scenario, the lightest Higgs is the observed Higgs particle at LHC ($h \equiv H_{SM}$). This can be achieved with or without decoupling of the other scalars. In this case, the Higgs couplings approach towards those of the standard model when $\cos(\beta - \alpha) \to 0$, whereas in the second scenario, the heavier CP-even state ($H \equiv H_{SM}$) is identified as the SM-like Higgs whose couplings to gauge bosons approach the SM limit when $\sin(\beta - \alpha) \to 0$. The focus of this study is
nearly alignment limit without decoupling. This choice is well motivated by the interesting phenomenology of the light charged and/or neutral Higgs in 2HDM, particularly in type-III. We promote here a new signature to search for charged Higgs boson, while taking advantage of the Yukawa-texture contribution in $H^\pm$ decay width. For that, we employ all the recent results from the searches of light scalars and the signal measurements from LHC at Run-1 and Run-2, while taking advantage of the significant increase of Luminosity and energy, which began with a collision energy of 8 TeV rising to 13 TeV.

The light charged Higgs is searched for in top quark decay channel, $t \to H^\pm b$, for $m_{H^\pm} < m_t - m_b$. The LHC experiments are looking for such a particle in the leptonic and quark-Charged Higgs decay channels, namely $\tau\nu$, $c\bar{s}$ and $t^*\bar{b}$. We recall that the previous searches in the decay channel $pp \to tH^\pm \to \tau^\pm\nu_\tau$ at Run-1, lead to upper limits on $B(t \to bH^\pm) \times B(H^\pm \to \tau\nu)$ in the mass range $m_{H^\pm} = 80 - 160$ GeV \cite{7, 14, 61}. Moreover, the CMS collaboration has also recently set an upper limit (2\% - 3\%) on $Br(t \to H^\pm b)$ for $80 \text{ GeV} < m_{H^\pm} < 160 \text{ GeV}$, while assuming $Br(H^\pm \to \tau\nu) = 100\%$ \cite{52}. In addition, ATLAS and CMS have set an upper limit of 20\% on $Br(t \to H^\pm b)$ for the case $Br(H^\pm \to c\bar{s}) = 100\%$ in the mass range of 90 GeV to 160 GeV \cite{52}.

| Scenario | $m_h$ [GeV] | $m_H$ [GeV] | $m_A$ [GeV] | $m_{H^\pm}$ [GeV] | $s_{\beta-\alpha}$ | $\tan \beta$ | $m_{l_2}^2$ |
|----------|-------------|-------------|-------------|------------------|-----------------|----------|-----------|
| $h$      | 125         | 135         | 220         | [50; 160]        | -0.98           | 0.5; 15  | $m_h^2 \tan \beta / (1 + \tan^2 \beta)$ |
| $H$      | 95          | 125         | 177         | [50; 160]        | -0.05           | 0.5; 15  | $m_H^2 \tan \beta / (1 + \tan^2 \beta)$ |

Table 3. 2HDM input parameters for both scenarios.
Table 4. The signal of charged Higgs production and its decays.

| Abbreviation | Expression |
|--------------|------------|
| $\sigma_{2H}(t + b + \mu\nu)$ | $2 \times \sigma(pp \to tt \to H^\pm b + t \to \mu\nu + bt)$ |
| $\sigma_{2H}(t + b + \tau\nu)$ | $2 \times \sigma(pp \to tt \to H^\pm b + t \to \tau\nu + bt)$ |
| $\sigma_{2H}(t + b + c\bar{s})$ | $2 \times \sigma(pp \to tt \to H^\pm b + t \to c\bar{s} + bt)$ |
| $\sigma_{2H}(t + b + t^* b)$ | $2 \times \sigma(pp \to tt \to H^\pm b + t \to t^* b + bt)$ |
| $\sigma_{2H}(t + b + W^(*) h)$ | $2 \times \sigma(pp \to tt \to H^\pm b + t \to W^(*) h + bt)$ |

4.1 Part-I: h Scenario

In this scenario, we assume that the Higgs-like particle is $h$ with $m_h = 125$ GeV. We perform a systematic scan over the 2HDM parameters as indicated in Table 3. After performing a scan over the 2HDM parameters, we show in Figure 2, the allowed region of parameter space in $(m_{H^\pm}, \tan \beta)$ plane by the theoretical and the current experimental bounds. The yellow and green regions are respectively excluded by LEP [62] and LHC searches (see Fig 9(left panel) in the Appendix). The dotted line indicates compatibility with the observed Higgs signal at $2\sigma$. The majority of the region is excluded by theoretical and experimental constrains as can be seen from Table 5, which demonstrates that only 4.31% of the parameter space is permitted. On the other hand, one can read from the same figure that small values of $\tan \beta$ are allowed for different masses of $H^\pm$ in type-III, unlike type-I which excludes small $\tan \beta$ for light $m_{H^\pm}$. Type-I is scrutinized by charged Higgs searches $H^\pm \rightarrow \tau\nu$ channel and by several flavour observables such as $\delta m_s$ and $B_{d,s} \rightarrow \mu^+\mu^-$ [63].

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Constraints on the $h \equiv SM$ scenario Type-III (left) and Type-I (right) from Higgs searches at the (LHC & LEP), in the $(m_{H^\pm}, \tan \beta)$ plane. The hatched area is excluded by a mismatch between the properties of $h$ and those of the observed Higgs boson, and the (green and yellow) areas are excluded by the searches for additional Higgs bosons.

We now examine the light charged Higgs decays in the framework of 2HDM type-III. The relaxing bounds on charged Higgs mass in this model is, in fact, due to the contribution of the non diagonal Yukawa couplings in the amplitude of the B meson decay, $\overline{B} \rightarrow X_s\gamma$. 

- 8 -
Figure 3 shows that the decay width of charged Higgs is not dominated by $H^\pm \rightarrow \tau \nu$ and $H^\pm \rightarrow t^* \bar{b}$ decays. The decay channel $H^\pm \rightarrow \mu \nu$ becomes the dominant decay mode over almost the whole allowed parameter space region, with a branching ratio of 80%. To understand the reason behind the dominance of $H^\pm \rightarrow \mu$ over the other fermionic channels $t^* \bar{b}$, $c\bar{s}$ and $\tau \nu$, we will study the effect of the contribution of the free parameters derived from the non diagonal elements of the Yukawa matrix on the charged Higgs width, we recall that the partial decay width of the Charged Higgs into two leptons is as follows:

$$\Gamma(H^\pm \rightarrow l_i^+ \nu_i) = \frac{G_F m_{H^\pm} m_{l_i}^2}{4\sqrt{2} \pi m_{H^\pm}^2} (\xi_A)_{ij}^2 \left(1 - \frac{m_{l_i}^2}{m_{H^\pm}^2}\right)^3 \tag{4.1}$$

where $i = j$, $m_l \ll m_{H^\pm}$ and $(\xi_A)_{ij} = \tan \beta - \frac{1}{\sqrt{2} \cos \beta} \chi_{ij}^l$.

![Figure 3](image)

**Figure 3.** The $BR(H^\pm \rightarrow XY)$ (up) and $\sigma_{2t}^{H^\pm}(t + b + XY)$ (down) mapped over the $(m_{H^\pm}, \tan \beta)$ plane. For $XY \equiv c\bar{s}$ (down left) and $XY \equiv \mu \nu$ (right). In each plot, the boundaries of the (green & yellow) and the hatched exclusion regions of Figure 2 are also shown as a dashed and a dotted black line, respectively.

Note that $|\chi_{22}^l| > |\chi_{11,33}^l|$, therefore the term $m_{H^\pm}^2 (\tan \beta - \frac{1}{\sqrt{2} \cos \beta} \chi_{22}^l)$ is dominant over the other couplings when the channel $H^\pm \rightarrow t^* \bar{b}$ is closed, especially $\tau \nu$. Furthermore, one can read from figure 2 that Type-III could predict large production rate of $\mu \nu$ and $c\bar{s}$ from charged Higgs decay, where $\sigma_{2t}^{H^\pm}(t + b + \mu \nu)$ and $\sigma_{2t}^{H^\pm}(t + b + c\bar{s})$ could reach values of 23...
pb and 6 pb respectively in the range of masses varying from 72 GeV to 150 GeV, due to the higher branching ratios of charged Higgs decays and its production rate from $pp \rightarrow t\bar{t}$ process.

\[ \sigma_{H^\pm}(l + b + \mu\nu) \text{ v.s. } \sigma_{H^\pm}(l + b + XY) \text{ with } XY \equiv \tau\nu \text{ (left) and } XY \equiv c\bar{s} \text{ (right).} \]

\[ \text{The color bar shows the mass of the charged Higgs boson (up) and } \tan\beta \text{ (down).} \]

**Figure 4.** $\sigma_{H^\pm}(l + b + \mu\nu)$ v.s $\sigma_{H^\pm}(l + b + XY)$ with $XY \equiv \tau\nu$ (left) and $XY \equiv c\bar{s}$ (right). The color bar shows the mass of the charged Higgs boson (up) and $\tan\beta$ (down).

In Figure 4, we show the correlation between production and decay of light charged Higgs into $\mu\nu$ and $\tau\nu$ (upper-left) and $cs$ (upper-right) mapping on charged Higgs mass $m_{H^\pm}$ (upper panels) and $\tan\beta$ (lower panels). It is clear from the plots that, $\sigma_{H^\pm}(l + b + \mu\nu)$ is about one order of magnitude larger for intermediate values of $\tan\beta$ and within 80 GeV to 120 GeV for charged Higgs mass. Clearly, we have checked that $BR(t \rightarrow H^\pm b) \times BR(H^\pm \rightarrow \tau\nu)$ is below the current limit from CMS and ATLAS and below 0.01%.

### 4.2 Part-II: $H$ Scenario

In this scenario, we assume that the Higgs-like particle is $H$ with $m_H = 125$ GeV, while $m_h$ is fixed at 95 GeV. We perform a systematic scan over the 2HDM parameters as indicated in Table 3. Figure 5 illustrates the allowed parameter space after taking into account most update theoretical and experimental constraints. In this configuration, a large region of
2HDM parameter space as well as large $\tan \beta$ are allowed, compared to the first configuration (standard hierarchy). In order to understand the allowed region, we plotted various contributions arising from different processes (see Figure 9 (left) in Appendix) due to parameter relations to constraint ($m_{H^\pm}, \tan \beta$) space. Most allowed region in Figure 5(left) comes from $pp \rightarrow gg \rightarrow A \rightarrow \mu^+\mu^-$ channel due to Yukawa coupling in 2HDM type-III framework. Note that most of scanned region is compatible with the observed Higgs boson state at 95\% C.L. Negative search comes from $pp \rightarrow tbH^\pm$ followed by $H^\pm \rightarrow \tau\nu$ at the LHC in 36.1 $fb^{-1}$ of data at $\sqrt{s} = 13$ TeV. Such limit exclude large parameter space in 2HDM type-I. As can be seen from table 5, the number of the allowed points, by theoretical and experimental constraints, is significant in the inverted hierarchy scenario, where 45\% of $10^6$ points are allowed after scanning over 2HDM parameter space. After analyzing the allowed parameter space regions, we study the charged Higgs decay in such scenario.

| Scenario | Allowed by theoretical constraints | Allowed by HiggsBounds | Allowed by HiggsSignals | Allowed by all constraints |
|----------|-----------------------------------|------------------------|-------------------------|---------------------------|
| $h$      | 62.33\%                          | 7.08\%                 | 26.4\%                  | 4.31\%                    |
| $H$      | 100\%                            | 45.08\%                | 90.2\%                  | 45.07\%                   |

Table 5. Details of the allowed points in parameter space after imposing theoretical and experimental constraints.

Figure 6 shows the branching ratios for the main decays of charged Higgs in 2HDM type-III. In such configuration, the $H^\pm \rightarrow W^{(*)}h$ channel could be open and thus it could strongly compete with the other channels like $\tau\nu, cs$ and $t^*b$, because of the enhancement of its coupling $hH^\pm W^\mp$ in the alignment limit. The charged Higgs decay width is dominated by the two channels $H^\pm \rightarrow W^{(*)}h$ and $H^\pm \rightarrow \mu\nu$ over the other fermionic channels. The
Figure 6. The BR($H^+ \rightarrow XY$) (up) and $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + XY)$ (down) mapped over the $(m_{H^\pm}, \tan\beta)$ plane. For $XY \equiv W^{(\ast)}h$ (left) and $XY \equiv \mu\nu$ (right). In each plot, the boundaries of the (green & yellow) and the hatched exclusion regions of Fig 5 are also shown as a dashed and a dotted black line, respectively.

former can reach a maximum width around 80% when the vector boson is being off shell, therefore the $H^\pm \rightarrow W^{(\ast)}h$ channel would be open, whereas $H^\pm \rightarrow \mu\nu$ becomes significant due to the contribution of the off diagonal elements in the Yukawa couplings. 2HDM type-III predicts then a scenario where $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + \mu\nu)$ becomes significant and yields 27 pb at 13 TeV for light $H^\pm$ and intermediate $\tan\beta$. On the other hand, $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + W^{(\ast)}h)$ is suppressed by the small production rate of charged Higgs via top decay for large $\tan\beta$.

As in Figure 7 (similar to Figure 4), we present the corresponding correlation from $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + \mu\nu)$ with $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + c\bar{s})$ and $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + \tau\nu)$ mapping on charged Higgs mass (upper panels) and on $\tan\beta$ (lower panels). It is clear that $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + \mu\nu)$ can order of magnitude over $\tau\nu$ and $c\bar{s}$ modes for roughly $m_{H^\pm}$ in 80 GeV ~120 GeV range and $\tan\beta$ in 2 ~ 5 range. It is therefore clear that $\sigma_{H^\pm}^{H^\pm}(\bar{t} + b + \mu\nu)$ can provide a potential alternative discovery channel for light charged Higgs boson at the LHC in the 2HDM-type-III.

4.3 Benchmark points

Table 6 summarizes some Benchmark Points (BPs) for each scenario. All these BPs satisfy the most update theoretical and experimental constraints. For every BP in the table, we
Figure 7. $\sigma_{t+b+\tau\nu}^{H^{\pm}}$ v.s $\sigma_{t+b+\mu\nu}^{H^{\pm}}$ with $XY \equiv \tau\nu$ (left) and $XY \equiv c\bar{s}$ (right). The color bar shows the mass of the charged Higgs boson (up) and $\tan\beta$ (down).

give the cross sections of $t+b+XY$, where $XY = cs, t^*b, W^{(*)}h, \tau\nu$ and $\mu\nu$ signatures. Furthermore, the production rate of $t+b+\mu\nu$ can reach few pico barn in scenario where $H$ is the SM state. Hence, in the standard hierarchy ($h$ is assumed SM-like), the aforementioned cross sections are still sizable.

5 Conclusions

With the addition of a Higgs doublet to the SM, we can address some basic issues of the SM, for instance the question of the structure of EWSBs, the flavor enigma, the possibility of the existence of an additional CP violation, the mechanics of EW baryogenesis, the identification of appropriate targets for dark matter (DM), etc. This extra addition of scalar doublet provides a general 2HDM, which makes it possible to obtain a more accurate picture of the nature. Charged Higgs sector of general 2HDM has been thoroughly investigated in the existing literature as well as an interpretation projection from experiments collaborations.
Table 6. Mass spectra, mixing angles, branching ratios and cross section (in pb) in each configuration

In this current work, we intended to explore the phenomenology of charged Higgs in 2HDM-type I and type-III, where the parameter region are similar, and both scenarios provide alternative ways to capture light charged Higgs. To be more accurate, the LHC collaborations are now in search of new states beyond the SM, such realization could be done in general 2HDM for example. The main advantage of generating $pp \rightarrow t \bar{t}$ process is twofold. Firstly, the large cross-section for top anti-top are produced via QCD interactions.
which do not rely on the 2HDM parameters. Secondly, top quark may interact with charged Higgs boson as \( t \to H^\pm b \) mode, where it is model dependent. Charged Higgs boson when produced, it may decay into standard particles. The so-called Yukawa couplings are related to the different manners by which the second Higgs doublet is realized beyond SM.

In this work, we have specifically focused on the production of charged Higgs bosons via \( pp \to tbH^\pm \) at the LHC with \( \sqrt{s} = 13 \) TeV in both 2HDM type-I and type-III. After considering all the up-to-date theoretical and experimental constraints, allowing \( H^\pm \to \mu \nu \) instead of standard decay mode \( H^\pm \to \tau \nu \), we have studied the final states \( t + b + \mu \nu \) as potential discovery channel. In doing so, we have compared the efficiency of that channels over a large range of charged Higgs mass, up to top quark mass when \( \tan \beta \) is intermediate. The most interesting regions of the 2HDM to types are explored to show significant potentially discoverable event rates. Therefore, with a view to letting the ATLAS and CMS collaborations either confirm or constraint this alternative, we eventually proposed a number of BPs in the following 2HDM type-I and -III final states that are suitable for further experimental investigation.
Appendix

Figure 8. Projection of our finding on ATLAS [11] and CMS[15] results.

Figure 9. The Allowed channels by all constraints for both configurations.
References

[1] ATLAS collaboration, G. Aad et al., “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. B716 (2012) 1-29, arXiv:1207.7214 [hep-ex].

[2] CMS collaboration, S. Chatrchyan et al., “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC”, Phys. Lett. B716 (2012) 30-61, arXiv:1207.7235 [hep-ex].

[3] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, “The Higgs Hunter’s Guide” Front. Phys. 80 (2000), 1-404 SCIPP-89/13.

[4] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, “Theory and phenomenology of two-Higgs-doublet models”, Phys. Rept. 516 (2012) 1-102, arXiv:1106.0034 [hep-ph].

[5] T. P. Cheng and M. Sher, “Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets”, Phys. Rev. D35 (1987) 3484.

[6] ATLAS collaboration, G. Aad et al., “Search for a light charged Higgs boson in the decay channel $H^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events using pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector”, Eur. Phys. J. C73 (2013) 2465, arXiv:1302.3694 [hep-ex].

[7] ATLAS collaboration, G. Aad et al., “Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector”, JHEP 1503 (2015) 088, arXiv:1412.6663 [hep-ex].

[8] ATLAS collaboration, M. Aaboud et al., “Search for charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \rightarrow \tau^\pm \nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector”, Phys. Lett. B759 (2016), 555-574, arXiv:1603.09203 [hep-ex].

[9] ATLAS collaboration, G. Aad et al., “Search for charged Higgs bosons in the $H^\pm \rightarrow tb$ decay channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector”, JHEP 03 (2016), 127, arXiv:1512.03704 [hep-ex].

[10] ATLAS collaboration, “Search for charged Higgs bosons decaying into a top-quark and a bottom-quark at $\sqrt{s} = 13$ TeV with the ATLAS detector”, ATLAS-CONF-2020-039.

[11] ATLAS collaboration, M. Aaboud et al., “Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu_e$ in the $\tau$+jets and $\tau$+lepton final states with 36 fb$^{-1}$ of pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS experiment”, JHEP 09 (2018) 139, arXiv:1807.07915 [hep-ex].

[12] ATLAS collaboration, G. Aad et al., “Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s} = 13$ TeV with the ATLAS detector”, JHEP 06 (2021), 145, arXiv:2102.10076 [hep-ex].

[13] ATLAS collaboration, M. Aaboud et al., “Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector”, JHEP 11 (2018) 085, arXiv:1808.03599 [hep-ex].

[14] CMS collaboration, V. Khachatryan et al., “Search for a charged Higgs boson in pp collisions at $\sqrt{s} = 8$ TeV”, JHEP 11 (2015) 018, arXiv:1508.07774 [hep-ex].

[15] CMS collaboration, A. M. Sirunyan et al., “Search for charged Higgs bosons in the $H^\pm \rightarrow \tau^\pm \nu_e$ decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV”, JHEP 07 (2019) 142, arXiv:1903.04560 [hep-ex].
[16] CMS collaboration, V. Khachatryan et al., “Search for a light charged Higgs boson decaying to c\bar{s} in pp collisions at \sqrt{s} = 8 TeV”, JHEP 12 (2015) 178, arXiv:1510.04252 [hep-ex].

[17] CMS collaboration, A. M. Sirunyan et al., “Search for a charged Higgs boson decaying to charm and bottom quarks in proton-proton collisions at \sqrt{s} = 8 TeV”, JHEP 11 (2018), 115, arXiv:1808.06575 [hep-ex].

[18] ATLAS collaboration, M. Aaboud et al., “Search for charged Higgs bosons decaying via H^\pm \rightarrow \tau^\pm\nu_\tau in the \tau+jets and \tau+lepton final states with 36 fb^{-1} of pp collision data recorded at \sqrt{s} = 13 TeV with the ATLAS experiment”, JHEP 09 (2018) 139, arXiv:1807.07915 [hep-ex].

[19] B. Coleppa, F. Kling and S. Su, “Charged Higgs search via AW^\pm/HW^\pm channel”, JHEP 12 (2014), 148, arXiv:1408.4119 [hep-ph].

[20] R. Enberg, W. Klemm, S. Moretti, S. Munir and G. Wouda, “Charged Higgs boson in the W^\pm Higgs channel at the Large Hadron Collider”, Nucl. Phys. B893 (2015) 420-442, arXiv:1412.5814 [hep-ph].

[21] F. Kling, A. Pyarelal and S. Su, “Light Charged Higgs Bosons to AW/HW via Top Decay”, JHEP 11 (2015) 051, arXiv:1504.06624 [hep-ph].

[22] A. G. Akeroyd, M. Aoki, A. Arhrib, L. Basso, I. F. Ginzburg, J. Hernandez-Sanchez, K. Huitu, T. Hurth and M. Kadastik, et al., “Prospects for charged Higgs searches at the LHC”, Eur. Phys. J. C77 (2017) 276, arXiv:1607.01320 [hep-ph].

[23] A. Arhrib, R. Benbrik and S. Moretti, “Bosonic Decays of Charged Higgs Bosons in a 2HDM Type-I”, Eur. Phys. J. C77 (2017) 621 arXiv:1607.02402 [hep-ph].

[24] D. S. M. Alves, S. El Hedri, A. M. Taki and N. Weiner, “Charged Higgs Signals in t\bar{t}H Searches”, Phys. Rev. D96 (2017) no.7, 075032, arXiv:1703.06834 [hep-ph].

[25] A. Arhrib, K. Cheung and C. T. Lu, “Same-sign charged Higgs boson pair production in bosonic decay channels at the HL-LHC and HE-LHC”, Phys. Rev. D102 (2020) no.9, 095026, arXiv:1910.02571 [hep-ph].

[26] A. Arhrib, R. Benbrik, H. Harouiz, S. Moretti, Y. Wang and Q. S. Yan, “Implications of a light charged Higgs boson at the LHC run III in the 2HDM”, Phys. Rev. D102 (2020) no.11, 115040, arXiv:2003.11108 [hep-ph].

[27] S. Kanemura and C. P. Yuan, “Testing supersymmetry in the associated production of CP odd and charged Higgs bosons”, Phys. Lett. B530 (2002), 188-196, arXiv:hep-ph/0112165 [hep-ph].

[28] Q. H. Cao, S. Kanemura and C. P. Yuan, “Associated production of CP odd and charged Higgs bosons at hadron colliders”, Phys. Rev. D69 (2004), 075008, arXiv:hep-ph/0311093 [hep-ph].

[29] A. Belyaev, Q. H. Cao, D. Nomura, K. Tobe and C. P. Yuan, “Light MSSM Higgs boson scenario and its test at hadron colliders”, Phys. Rev. Lett. 100 (2008), 061801, arXiv:hep-ph/0609079 [hep-ph].

[30] H. Bahl, T. Stefaniak and J. Wittbrodt, “The forgotten channels: charged Higgs boson decays to a W and a non-SM-like Higgs boson”, JHEP 06 (2021), 183, arXiv:2103.07484 [hep-ph].

[31] A. Ferrari and N. Rompotis, “Exploration of Extended Higgs Sectors with Run-2 Proton–Proton Collision Data at the LHC”, Symmetry 13 (2021) no.11, 2144.

[32] A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti, Y. Wang and Q. S. Yan, “New discovery modes for a light charged Higgs boson at the LHC”, JHEP 10 (2021), 073, arXiv:2106.13656 [hep-ph].

[33] Y. Wang, A. Arhrib, R. Benbrik, M. Krab, B. Manaut, S. Moretti and Q. S. Yan, “Analysis of W^\pm + 4\gamma in the 2HDM Type-I at the LHC”, arXiv:2107.01451 [hep-ph].
[34] A. Arhrib, R. Benbrik, R. Enberg, W. Klemm, S. Moretti and S. Munir, “Identifying a light charged Higgs boson at the LHC Run II”, Phys. Lett. B774 (2017), 591-598, arXiv:1706.01964 [hep-ph].

[35] R. Enberg, W. Klemm, S. Moretti and S. Munir, “Electroweak production of multiple (pseudo)scalars in the 2HDM”, Eur. Phys. J. C79 (2019) no.6, 512, arXiv:1812.01147 [hep-ph].

[36] R. Enberg, W. Klemm, S. Moretti and S. Munir, “Signatures of the Type-I 2HDM at the LHC”, PoS CORFU2018 (2018), 013, arXiv:1812.08623 [hep-ph].

[37] J. L. Diaz-Cruz, R. Noriega-Papaqui and A. Rosado, “Mass matrix ansatz and lepton flavor violation in the THDM-III”, Phys. Rev. D69 (2004) 095002, arXiv:hep-ph/0401194 [hep-ph].

[38] S. Kanemura, T. Kubota and E. Takasugi, “Lee-Quigg-Thacker bounds for Higgs boson masses in a two doublet model”, Phys. Lett. B313 (1993) 155-160, arXiv:hep-ph/9303263 [hep-ph].

[39] A. G. Akeroyd, A. Arhrib and E. M. Naimi, “Note on tree level unitarity in the general two Higgs doublet model”, Phys. Lett. B490 (2000) 119-124, arXiv:hep-ph/0006035 [hep-ph].

[40] A. Arhrib, “Unitarity constraints on scalar parameters of the standard and two Higgs doublets model”, arXiv:hep-ph/0012353 [hep-ph].

[41] A. Barroso, P. M. Ferreira, I. P. Ivanov and R. Santos, “Metastability bounds on the two Higgs doublet model”, JHEP 06 (2013), 045, arXiv:1303.5098 [hep-ph].

[42] N. G. Deshpande and E. Ma, “Pattern of Symmetry Breaking with Two Higgs Doublets”, Phys. Rev. D18 (1978) 2574.

[43] W. Grimus, L. Lavoura, O. M. Ogred and P. Osland, “A Precision constraint on multi-Higgs-doublet models”, J. Phys. G35 (2008), 075001, arXiv:0711.4022 [hep-ph].

[44] W. Grimus, L. Lavoura, O. M. Ogred and P. Osland, “The Oblique parameters in the multi-Higgs-doublet models”, Nucl. Phys. B801 (2008) 81-96, arXiv:0802.4353 [hep-ph].

[45] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer and J. Stelzer, “Update of the global electroweak fit and constraints on two-Higgs-doublet models”, Eur. Phys. J. C78 (2018) no.8, 675, arXiv:1803.01853 [hep-ph].

[46] P. Bechtle, D. Dercks, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein and J. Wittbrodt, “HiggsBounds-5: Testing Higgs Sectors in the LHC 13 TeV Era”, Eur. Phys. J. C80 (2020) 1211, arXiv:2006.06007 [hep-ph].

[47] P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak and G. Weiglein, “Applying Exclusion Likelihoods from LHC Searches to Extended Higgs Sectors”, Eur. Phys. J. C75 (2015) no.9, 421, arXiv:1507.06706 [hep-ph].

[48] P. Bechtle, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein and J. Wittbrodt, “HiggsSignals-2: Probing new physics with precision Higgs measurements in the LHC 13 TeV era”, Eur. Phys. J. C81 (2021) 145, arXiv:2012.09197 [hep-ph].

[49] F. Mahmoudi, “SuperIso v2.3: A Program for calculating flavor physics observables in Supersymmetry”, Comput. Phys. Commun. 180 (2009) 1579-1613, arXiv:0808.3144 [hep-ph].

[50] R. Aaij et al. [LHCb], “First Evidence for the Decay $B_0^0 \rightarrow \mu^+\mu^-$”, Phys. Rev. Lett. 110 (2013) no.2, 021801, arXiv:1211.2674 [hep-ex].

[51] R. Aaij et al. [LHCb], “Measurement of the $B_0^0 \rightarrow \mu^+\mu^-$ branching fraction and effective lifetime and search for $B^0 \rightarrow \mu^+\mu^-$ decays”, Phys. Rev. Lett. 118 (2017) no.19, 191801, arXiv:1703.05747 [hep-ex].

– 19 –
[52] Particle Data Group, M. Tanabashi et al., “Review of Particle Physics”, Phys. Rev. D98 (2018) 030001.

[53] K. S. Babu and C. F. Kolda, “Higgs mediated $B^0 \rightarrow \mu^+ \mu^-$ in minimal supersymmetry”, Phys. Rev. Lett. 84 (2000), 228-231, arXiv:hep-ph/9909476 [hep-ph].

[54] HFLAV collaboration, Y. Amhis et al., “Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2016”, Eur. Phys. J. C77 (2017) 895, arXiv:1612.07233 [hep-ex].

[55] D. Eriksson, J. Rathsman and O. Stal, “2HDMC: Two-Higgs-Doublet Model Calculator Physics and Manual,” Comput. Phys. Commun. 181 (2010) 189-205, arXiv:0902.0851 [hep-ph].

[56] CMS collaboration, A. M. Sirunyan et al., “Search for a light charged Higgs boson decaying to a $W$ boson and a CP-odd Higgs boson in final states with $ee\mu\mu$ or $\mu\mu\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, Phys. Rev. Lett. 123 (2019) 131802, arXiv:1905.07453 [hep-ex].

[57] CMS collaboration, A. M. Sirunyan et al., “Search for charged Higgs bosons decaying into a top and a bottom quark in the all-jet final state of pp collisions at $\sqrt{s} = 13$ TeV”, JHEP 07 (2020) 126, arXiv:2001.07763 [hep-ex].

[58] CMS collaboration, A. M. Sirunyan et al., “Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, Phys. Rev. Lett. 120 (2018) 231801, arXiv:1804.02610 [hep-ex].

[59] J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, “Scrutinizing the alignment limit in two-Higgs-doublet models. II. $m_H=125$ GeV”, Phys. Rev. D93 (2016) 035027, arXiv:1511.03682 [hep-ph].

[60] J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, “Scrutinizing the alignment limit in two-Higgs-doublet models: $m_h=125$ GeV”, Phys. Rev. D92 (2015) 075004, arXiv:1507.00933 [hep-ph].

[61] CMS collaboration, “Search for charged Higgs bosons with the $H^\pm \rightarrow \tau^\pm \nu_\tau$ decay channel in the fully hadronic final state at $\sqrt{s} = 13$ TeV”, CMS-PAS-HIG-16-031.

[62] ALEPH, DELPHI, L3, OPAL and LEP collaboration, G. Abbiendi et al., “Search for Charged Higgs bosons: Combined Results Using LEP Data”, Eur. Phys. J. C73 (2013) 2463, arXiv:1301.6065 [hep-ex].

[63] CMS collaboration, A. M. Sirunyan et al., “Observation of $t\bar{t}H$ production”, Phys. Rev. Lett. 120 (2018) 231801, arXiv:1804.02610 [hep-ex].

[64] CMS collaboration, A. M. Sirunyan et al., “Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV”, Phys. Lett. B793 (2019) 320-347, arXiv:1811.08459 [hep-ex].

[65] F. Kling, S. Su and W. Su, “2HDM Neutral Scalars under the LHC”, JHEP 06 (2020), 163, arXiv:2004.04172 [hep-ph].

[66] N. Chen, T. Han, S. Li, S. Su, W. Su and Y. Wu, “Type-I 2HDM under the Higgs and Electroweak Precision Measurements”, JHEP 08 (2020), 131, arXiv:1912.01431 [hep-ph].

[67] M. E. Peskin and T. Takeuchi, “Estimation of oblique electroweak corrections”, Phys. Rev. D46 (1992) 381-409.

[68] H. J. He, N. Polonsky and S. f. Su, “Extra families, Higgs spectrum and oblique corrections”, Phys. Rev. D64 (2001) 053004, arXiv:hep-ph/0102144 [hep-ph].
[69] H. E. Haber and D. O’Neil, “Basis-independent methods for the two-Higgs-doublet model III: The CP-conserving limit, custodial symmetry, and the oblique parameters S, T, U”, Phys. Rev. D83 (2011) 055017, arXiv:1011.6188 [hep-ph].

[70] Heavy Flavor Averaging Group (HFAG), Y. Amhis et al., “Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014”, arXiv:1412.7515 [hep-ex].

[71] F. Archilli, “$B_s^0 \to \mu^+\mu^-$ at LHC”, arXiv:1411.4964 [hep-ex].