Charged Higgs Phenomenology in di-bjet channel with $H^\pm \to W^\pm h$ in 2HDM Type-II using Machine Learning Technique

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(Dated: August 8, 2022)

The latest LHC collaborations results on $\sigma_{H^\pm}BR(H^\pm \to \tau^\pm \nu)$ and $\sigma_{H^\pm}BR(H^\pm \to t\bar{b})$ are used to impose constraints on the charged Higgs $H^\pm$ parameters within the Two Higgs Doublet Model (2HDM). But it leaves 1.5 $\leq \tan\beta \leq 3$ window unexplored where the $BR(H^\pm \to W^\pm h)$ becomes sizable for $m_{H^\pm} > m_t$. In this manuscript $H^\pm \to W^\pm h$ is investigated with neutral Higgs boson decaying to a pair of b-quarks and the discovery prospects of charged Higgs boson is discussed. In particular, the analysis is optimized by putting the kinematic cuts and prospects of using Machine Learning Technique to derive values of $\sigma \times BR$ needed for a $5\sigma$ discovery at the LHC.

Keywords: Standard Model, Charged Higgs boson, cross section, branching ratios, mixing angle, $\tan\beta$

I. INTRODUCTION

The Standard Model (SM) of particle physics describes with high accuracy a multitude of experimental and observational data ranging ranging from the smallest energy scales up to the scale of several TeV set by the center-of-mass energy of the Large Hadron Collider (LHC) at CERN. With the recent discovery of the Higgs boson[1][2], the particle content of the SM corresponds to a renormalizable theory and is in this sense complete. Nevertheless, the SM does not accommodate phenomena such as gravity or dark matter and dark energy inferred from cosmological observations, prompting theoretical work on its extensions. Over the years, many models addressing these shortcomings purport to go "beyond the Standard Model (BSM)". These models predict new particles in the form of new heavy vector, scalar or fermion resonances which can potentially be observed at the CERN LHC.

On the earliest BSM scenarios to emerge was Technicolor (TC)[3] but these did not rely on the existence of fundamental scalar particle (Higgs). With the discovery of the Higgs boson at CERN LHC implies the Higgsful extension of the SM. One of the simplest extensions of the Standard Model (SM) Higgs sector is the Two-Higgs-Doublet Model (2HDM). A recent measurements from the B-Factor experiments BABAR, Belle and LHCb have reported large disagreements (at the 3.9$\sigma$ level) in semi-tauonic decays ($B \to \tau\nu$) involving ratios of charmed final states[4][5]. This disagreement is an interesting anomaly that deserves more experimental and theoretical study, in particular due to the absence of any clear new physics signal from the experiments at the energy frontier of particle physics. One of the possible explanation is the existence of BSM charged Higgs ($H^\pm$) can enhance this particular decay.

This manuscript is organized as follows: Section II presents the necessary details of the model under investigation. Section III A discusses the production mechanism and the decays of the charged Higgs in this model. Section III B presents the current bounds and in Section III C the discovery prospects of Charged Higgs is presented based on kinematic cuts while Section III D presents the setup for Machine Learning technique. The manuscript concludes in Section IV with a summary of the key results.

II. TWO-HIGGS-DOUBLET MODEL

This section presents an overview of the two-Higgs-doublet model (2HDM) that will be used as an operating example of our phenomenological model. The discussion here is very brief, only touching the parts relevant to this manuscript. A comprehensive review of this model is given in ref[8]. The scalar potential for two doublets $\Phi_1$ and $\Phi_2$ with hypercharge +1 is

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c$$

(1)

where all the parameters are real for simplicity. The complex scalar doublets $\Phi_i(i = 1,2)$ can be parametrized as

$$\Phi_i(x) = \left( \begin{array}{c} \phi^+_i(x) \\ -\sqrt{2}(v_i + \rho_i(x) + \eta_i(x)) \end{array} \right)$$

(2)

with $v_1, v_2 \geq 0$ being VEVs satisfying $v = \sqrt{v_1^2 + v_2^2} = 246.22$ GeV. After electroweak symmetry breaking (EWSB), three of the eight degrees of freedom in the
Table I. The expressions for \( g_{qH^\pm}^2 \) in the 2HDMs Type-I & II considered in this paper.

|                | 2HDM-I          | 2HDM-II         |
|----------------|-----------------|-----------------|
| \( g_{qH^\pm}^2 \) | \( m_t^2 \cot^2 \beta + m_b^2 \cot^2 \beta \) | \( m_t^2 \tan^2 \beta + m_b^2 \cot^2 \beta \) |

Higgs sector of the 2HDM are eaten by the Goldstone boson which give mass to \( W^\pm \) and \( Z \). The remaining five becomes physical Higgs boson. After the minimization of the potential, the 2HDM has seven independent parameters.

\( m_h, m_H, m_A, m_{H^\pm}, \alpha, \tan \beta, m_t^2 \)

where \( \tan \beta = \frac{v_2}{v_1} \) and \( \alpha \) is the mixing angle. Of the particular interest to this manuscript is \( m_{H^\pm} \).

III. COLLIDER PHENOMENOLOGY

A. Cross sections, decay rates and search strategy

The feasible study of \( H^\pm \rightarrow hW^\pm \) is begun by setting up calculations and specific search strategy is employed. Putting constraint on \( \sin(\beta - \alpha) \) automatically implies the model dependent search but the analysis will be presented in a more general framework without recourse to the specific model discussed in section 2. The first step in the analysis is the identification of the production and decay modes. The dominant production process at the LHC for a \( H^\pm \) heavier than the top quark is its associated production with a single top, with the relevant sub-processes being \( gb \rightarrow tH^\pm \) and \( gg \rightarrow tbH^- \) (plus charge conjugated channel). The spin/color summed/averaged squared amplitude for the \( gb \rightarrow tH^- \) production process is given ref[9]

\[
|\mathcal{M}|^2 = \frac{g_{gH^\pm \pm}^2 g_W^2}{4m_N} |V_{tb}|^2 \left( \frac{u - m_T^2}{s(m_T^2 - t)} \right)^2 \left[ 1 + 2 \frac{m_H^2}{u} - m_H^2 + \frac{m_H^2}{u - m_H^2} \right] \left[ 1 + \frac{m_t^2}{u} - \frac{m_t^2}{u - m_H^2} \right] \]

where \( g_a \) and \( g_2 \) are the \( SU(3)_C \) and \( SU(2)_C \) gauge couplings, \( N_c = 3 \) is the number of colours and \( V_{tb} \) is the relevant CKM matrix element. The coupling \( g_{gH^\pm} \) is the model dependent parameter. The expression for \( g_{gH^\pm}^2 \) in the different 2HDM are in Table-I[10].

From Fig. 1, the amplitude for 2HDM Type-II for the \( gb \rightarrow tH^- \) process is maximal for either small or large \( \tan \beta \). Fig. 2 show the phase-space between the minimum value of the charged Higgs and \( \tan \beta \). For both Type-I & Type-II, \( \tan \beta \leq 2 \) is the feasible region for the minimum value of the charged Higgs boson. While Fig. 3 displays the experiments constraints on \( \tan \beta \) vs \( m_{H^\pm} \) proposed by the Belle Detector. The decay however can proceed via multiple mechanism depending on the strength of couplings in the particular model, and availability of phase space. The light charged Higgs boson would decay almost exclusively into a (hadronic or leptonic) \( \tau \) lepton and its associated neutrino for \( \tan \beta \geq 1 \). When the top-bottom channel is kinematically open, then \( H^\pm \rightarrow tb \) would compete with \( H^\pm \rightarrow hW^\pm, H^\pm \rightarrow AW^\pm \) decay as well various SUSY channel in the MSSM. At the tree level, the decay width of \( H^\pm \rightarrow W^\pm h \) is given by equation 4. The strength of \( hW^\pm \) channel is proportional to \( \cos^2(\beta - \alpha) \) and it is therefore absent for \( \sin(\beta - \alpha) = 1 \).

\[
\Gamma(H^\pm \rightarrow W^\pm h) = \frac{\lambda^{3/2}(m_H^2, m_W^2, m_h^2)}{64\pi m_H^2 m_W^2} \frac{c^2}{\sin^2\beta_W} \cos^2(\beta - \alpha)
\]

\[
\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz
\]

(4)

Figure 1. Coupling \( g_{gH^\pm}^2 \) vs \( \tan \beta \) for Type-I and Type-II 2HDM

Figure 2. 95% C.L. lower bounds on \( M_{H^\pm} \) as functions of \( \tan \beta \). Above \( \tan \beta \approx 2 \), the Model I bound becomes weaker than the LEP one (\( \approx 80 \) GeV), while the Model II one gets saturated by its \( \tan \beta \rightarrow \infty \) limit (\( \approx 580 \) GeV).[11]
The further constraints on $\cos(\beta - \alpha)$ for both 2HDM Type-I and 2HDM Type-II are given in (a) and (b) of Fig. 5 in ref [13]. Based on recent LHC and Belle collaborations results discussed in Section 3.1, we choose $\tan \beta = 1.3$ and $\sin(\beta - \alpha) = 0.7$ for the phenomenological study in the 2HDM Type-II model. A similar study of the allowed parameter space of the new physics models, knowledge of the mass of observed Higgs also provides an additional handle in identifying the $H^{\pm} \to W^{\pm} h$ decay. In this manuscript the $h \to bb$ is focused as it generally has a substantial branching ratio (BR) and allows for a full reconstruction of Higgs boson.

B. Experimental limits

The LEP experiments [15] have given limits on the mass of the charged Higgs boson in 2HDM from the charged Higgs searches in Drell–Yan events, $e^+ e^- \to Z/\gamma \to H^+ H^-$, excluding $m_{H^\pm} \leq 80$ GeV (Type II) and $m_{H^\pm} \leq 72.5$ GeV (Type I) at 95% confidence level. The Heavy Flavor Averaging Group (HFAG) [17] the $B \to X_s \gamma$ decay puts a very strong constraint on Type II and Type Y 2HDM, excluding $m_{H^\pm} \leq 580$ GeV. At the LHC several searches have been carried out for $H^\pm$’s lighter as well as heavier than the top quark. The CMS collaboration has recently released exclusion limits [18] for a $H^\pm$ lying in the mass range (180-600) GeV in $gg \to tH^\pm b$ production modes and in $H^\pm \to tb$ and $H^\pm \to t\nu$ decay modes based on 19.7 $fb^{-1}$ of data collected at $\sqrt{s} = 8$ TeV. The analysis [19] based on same dataset via $tt \to H^{\pm} W^{\pm} bb$ production mode and in the $H^\pm \to \tau \nu$ channel provides an exclusion limit of 80 GeV $\leq m_{H^\pm} \leq 160$ GeV. The ATLAS Collaborations [20] based on 19.5 $fb^{-1}$ dataset at $\sqrt{s} = 8$ TeV for the same production and decay modes provides an exclusion limits for 80 GeV $\leq m_{H^\pm} \leq 160$ GeV and 180 GeV $\leq m_{H^\pm} \leq 1$ TeV.

The two dominant decay channel, $tb$ and $\tau \nu$ leave $1.5 \leq \tan \beta \leq 3$ window unexplored for $m_{H^\pm} > m_t$. For the smaller values of $\tan \beta$, the $BR(H^\pm \to W^{\pm} h)$ becomes sizable as shown in Fig. 6 for $\tan \beta = 1$ and $\sin(\beta - \alpha) = 0.7$. Here, two light neutral Higgs bosons $h$ and $H$ (125 and 130 GeV) are considered.

C. Search prospects at LHC

After setting the required input parameters, the complete channel chosen to study the prospects of discovery is $pp \to H^\pm t \to jll\nu bbbb$, where $H^\pm \to W^{\pm} h$. The charged Higgs boson is produced via $gb \to H^\pm t$. The process $h \to bb$ has the largest branching ratio which is nearly 0.57% but suffers from high backgrounds from QCD multi-jet. On the other hand, the leptonic decay of W boson lowers the background. The Feynman diagram corresponding to the dominant production process and the final decay channels used in our analysis is shown in Fig. 5. The production cross section depends on the coupling $g_{Ht}$, to get an idea of the numbers involved, Fig. 4 shows the production cross-section for the benchmarks region 300-800 GeV. The data simulation
Figure 5. Feynman diagram showing the dominant production of Charged Higgs from $gb \rightarrow tH^\pm$ and $jjbbbl\nu$ final states. The Feynman diagram is drawn using JaxoDraw software[21].

Figure 6. Charged-Higgs boson production cross-section with $\tan\beta = 1$ and $\sin(\beta - \alpha) = 0.7$. Here, two light neutral Higgs bosons $h$ and $H$ (125 and 130 GeV) are considered.

Figure 7. Transverse momentum of the leading jet for both signal and background.

Figure 8. Transverse hadronic energy $H_T$ distribution for both signal and background.

Figure 9. The invariant mass distribution $M_{bb}$ for both the signal (corresponding to $M_h = 125$ GeV) and the background.

Figure 10. The invariant mass distribution $M_{b\bar{b}jj}$ for both the signal (corresponding to $M_{H^\pm} = 500$ GeV) and the background.
Table II. Cut flow chart showing the number of events after passing the cut selection

| Cut selection | Signal | ttbar+jets | t+jets | ZZ+jets | WZ+jets | WW+jets | Z+jets | W+jets | $\sqrt{s}$ |
|---------------|--------|------------|--------|---------|---------|---------|--------|--------|----------|
| Initial       | 30000  | 70000      | 50000  | 50000   | 50000   | 50000   | 50000  | 50000  | 47.43    |
| $3 \leq N_{jets} \leq 10$ | 29588  | 67674      | 48546  | 49432   | 43670   | 42655   | 42910  | 41332  | 48.92    |
| $N_{bjets} \geq 3$ | 9729   | 5250       | 1207   | 131     | 224     | 52      | 31     | 34     | 75.38    |
| $MET \geq 20$ GeV | 9138   | 4857       | 1110   | 70      | 204     | 46      | 21     | 29     | 73.46    |
| $H_T \geq 250$ GeV | 9132   | 4833       | 1048   | 69      | 187     | 44      | 19     | 24     | 73.69    |

Figure 11. Neural network response for the training and test samples for signal against t+jets background

Figure 12. ROC curve for the training and test samples for signal against t+jets background

Figure 13. Neural network response for the training and test samples for signal against ttbar+jets background

Figure 14. ROC curve for the training and test samples for signal against ttbar+jets background

For the $pp \rightarrow H^\pm \rightarrow W^\pm h \rightarrow jjbb$ signal, the dominant background comes from ttbar+jets, t+jets,
distribution that corresponds to the decay of charged Higgs boson of mass 500 GeV. Fig. 8 shows the transverse hadronic energy which has higher spread in the signal events. This prompts us to choose \( H_T > 250 \text{ GeV} \) to eliminate the SM backgrounds. The invariant mass distribution for the pair of b quarks is displayed in Fig. 9. It shows that there is significant overlap between signal and background making the \( M_{b\bar{b}} \) observable unimportant in discriminating signal from background. Finally we turn to the final step in the process of isolating the events in the \( M_{b\bar{b}j_1j_2} \) distribution that corresponds to the decay of charged Higgs boson which is displayed in Fig. 10. In both \( M_{b\bar{b}j_1j_2} \) and \( M_{b\bar{b}j_1j_2} \) cases, the signal and SM background overlap to a large extent making the job of isolating the signal from the backgrounds difficult.

Finally we present in Table II, the complete cut flow chart that details the impact of each of the kinematic cuts employed on both signal and the various backgrounds. The set of kinematic cuts are: \( 10 \leq N(j) \leq 10, N(b) \geq 3, \) missing transverse energy (MET) \( \geq 20 \text{ GeV}, \) total transverse hadronic energy \( (H_T) \geq 250 \text{ GeV}. \) Since a cut on \( M_{b\bar{b}j_1j_2} \) and \( M_{b\bar{b}j_1j_2} \) reduces signal by a large extent, it is not applied despite making the discovery prospects higher. As can be seen in Table II, the progressive cuts have done a good job in systematically suppressing the SM background. The kinematic cuts reduce the background by 98% while signal is also lost by 69%. But the large overlap of the signal and background prompts us to search beyond kinematic cuts based analysis to the era of Machine Learning Techniques.

### D. Setup for Machine Learning

Here, in this article, we feed-forward multi-layer artificial Neural Network (ANN) with back-propagation is used. Supervised learning with 50 nodes, 3 hidden layers, and elu activation function for input layers, relu for hidden layers and sigmoid activation function for output layers are used for training for the signal against background. The binary crossentropy (BCE) is used for calculating the loss. Batch normalization and dropout is used to increase the efficiency of the Networks. The input features are the transverse momentum, energy and eta of the jets, b-tagged jets, leptons and the recon-
Table III. Number of events after passing the Neural Network output cut.

| Cut selection | Signal | t+ jets | tbar+jets | ZZ+jets | WZ+jets | WW+jets | Z+jets | W+jets | $\sqrt{S} + B$ |
|---------------|--------|---------|-----------|---------|---------|---------|--------|--------|-------------|
| Initial       | 30000  | 70000   | 50000     | 50000   | 50000   | 50000   | 50000  | 50000  | 47.43       |
| NN Output > 0.5 | 23441  | 19483   | 11060     | 9858    | 13701   | 11205   | 9278   | 6020   | 72.67       |

Fig. 11 and Fig. 13 shows the Neural Network response for the signal against background t+jets and tbar+jets respectively. The corresponding receiver operating characteristic (ROC) curve are shown in Fig. 12 and Fig. 14. The area under the curve (AUC) for training against t+jets is larger than training against tbar+jets which shows that the Network response for t+jets is more efficient than tbar+jets. But the training against t+jets predicts more signal like response for tbar+jets as shown in Fig. 15. Fig. 16 shows the Neural Network prediction for all the SM backgrounds when trained against tbar+jets. It is seen that there is clear demarcation between the SM background and the signal. Thus cut is made on the Neural Network output and the number of events passing the cut are shown in Table III along with the significance. The applied cut reduces the background by 78% while losing the signal only by 21%.

IV. CONCLUSIONS

The discovery of SM-like 125 GeV Higgs at the ATLAS and CMS experiments motivates us to understand the potential of these experiments to unravel signatures of new physics. The various well motivated extensions of the SM incorporate an enlarged scalar sector with additional charged and neutral Higgs boson. In this article, first various experimental results from Belle and LHC collaborations that put constraints on external parameters of 2HDM Type-II model such as $m_{H^\pm}$ and $\tan \beta$ are discussed. Then a collider analysis in the experimentally unexplored region is performed to understand the discovery potential of a charged Higgs boson. The dominant QCD multi-jet background such as tbar+jets and t+jets were difficult to separate based on kinematic cuts. An advanced method such as Artificial Neural Network training with transverse momentum, energy and eta of the jets, b-tagged jets, and leptons as input features is used. This technique separates signal from background based configuration of the hyperspace parameters. It was found that the kinematic cuts based analysis reduces the background by 98% while losing large signal neraly 69%. Despite the huge constraint on the background, there lies a large overlap of both signal and background region. The applied Machine Learning Technique reduces the signal by 78% while losing the signal only by 21% and there lies distinct separation between the signal and background. This method provides large statistics after cuts for further analysis which will reduce the statistical uncertainties. The Neural Network output cut on 0.5 gave the significance of 72.67 which gives the large prospects of 5$\sigma$ discovery at Collider experiments.

While the search for charged Higgs is going on at LHC and Belle in full force, it is right time to for signatures that might be hidden from us. This paper summarizes the search strategy that one could employ to discover charged Higgs boson that could be part of the spectrum of a class of models.

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