Distinguishing charged Higgs bosons from different representations at the LHC

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ABSTRACT: Extending the Standard Model (SM) scalar sector via the addition of one or more Higgs fields in higher dimensional representations adds one or more charged Higgs bosons to the spectrum. Some of these gauge representations with appropriate hypercharge contain doubly-charged Higgs bosons and can be easily distinguished from the models that contain only singly-charged Higgs bosons. In this study we focus on the more challenging question of distinguishing singly-charged Higgs bosons from different representations, viz. doublets and triplets of the $SU(2)_L$ gauge group. We consider a supersymmetric extension of the SM with a gauge singlet and an $SU(2)_L$ triplet with $Y = 0$ as a benchmark scenario which has rich phenomenological possibilities due to the presence of a light pseudoscalar associated with the Z_3 symmetric superpotential. A detailed collider simulation considering all SM backgrounds has been carried out in order to determine which final states are more favourable for observing charged Higgs boson from particular representations as compared with others. We show that different representations can be probed and distinguished via singly-charged Higgs boson phenomenology at the $14\,\mathrm{TeV}$ LHC with an earliest data of $\sim 50\,\mathrm{fb}^{-1}$ of integrated luminosity.

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Contents

1 Introduction

In 2012 the ATLAS [1] and CMS [2] collaborations announced the discovery of a new elementary particle which was the candidate Higgs boson. This particle was the missing part of the Standard Model (SM) of particle physics. The ATLAS and CMS collaborations found a 125 GeV mass resonance with the properties that are mostly of the SM Higgs boson. The role of the Higgs boson in the SM is to give mass to all the elementary particles, apart from the photon and the gluon, through the mechanism of spontaneous symmetry breaking (SSB). The discovery made at the Large Hadron Collider (LHC) has revealed that the SSB mechanism is realised in a gauge theory such as the SM by at least one Higgs doublet. However, the possible existence of other scalar bosons cannot be excluded. This is mainly due to the not yet measured self interactions of the Higgs boson. Clearly, they are essential in order to establish the mechanism of electroweak symmetry breaking (EWSB), which is crucial in the SM dynamics, with better precision.

In spite of its success in the explanation of the properties of the known elementary particles, the SM is not a completely satisfactory theory. There are, in fact, long-standing issues, such that the gauge-hierarchy problem, the cold dark matter candidate, the masses of the neutrinos etc., to which the SM does not provide a satisfactory answer.

In this article we are interested in extensions of Higgs sector via various possible gauge representations. In principle these extensions are possible both with and without supersymmetry but in this analysis we consider only the supersymmetric ones. However the Higgs phenomenology and the non-standard decays are similar in both the cases. The interesting fact is that any extension of SM other than with a singlet superfield which takes part in EWSB gives rise to, at least, one physical massive charged Higgs boson. In the case of minimal supersymmetric extension of SM (MSSM) we have two Higgs doublets with opposite hypercharge which results in a physical charged Higgs bosons $h^{\pm}$. We refer to such a charged Higgs boson as a doublet-type charged Higgs boson and its coupling to SM fermions are given by Yukawa couplings and $\tan\beta$, the ratio of the vevs of the two Higgs doublets [3].

The other possibilities come from the triplet representation of SU(2). It is possible to include triplet(s) with $Y = 0$, $Y = \pm 1$ or both [4]. Each of them has its own signature, apart from addition of one or more charged Higgs bosons to the spectrum. The simplest extension is with a $Y = 0$ triplet which gives rise to two more physical charged Higgs bosons after the EWSB [5, 6]. Such extension is constrained by the ρ parameter [7] because the SU(2) triplet with $Y = 0$ hypercharge contributes to the tree-level mass of the $W^{\pm}$ gauge boson but not to the Z one. The vev of the $Y = 0$ triplet, which breaks the custodial symmetry, is then restricted to $\lesssim 5\,\mathrm{GeV}$ [5, 6]. Breaking of custodial symmetry leads to the non-standard signature of $h^{\pm} \to ZW^{\pm}$ which is very typical of triplet extension [5, 6].

As we already mentioned it is also possible to consider triplet(s) with non-zero hypercharge. Such extensions not only lead to triplet-like charged Higgs bosons but also predict the existence of doubly charged Higgs bosons [8]. These extensions also break the custodial symmetry and hence the triplet vevs are also restricted by the ρ parameter, similarly to the $Y = 0$ scenario. However a combination of $Y = 0$ and $Y = \pm 1$ can restore the custodial symmetry, as was shown by Georgi-Machacek [9] and has also been studied in the supersymmetric context [10].

The charged Higgs boson phenomenology can be largely affected by the existence of a very light scalar (CP-even or CP-odd), e.g. the next-to-Minimal Supersymmetric Standard Model (NMSSM) [11]. In this case $h^{\pm} \to a_1 W^{\pm}$ is kinematically allowed for a light charged Higgs boson with mass $\lesssim 200\,\mathrm{GeV}$. In a Z_3 symmetric superpotential, e.g. the NMSSM, such light pseudoscalar is a pseudo Nambu-Goldstone (pNG) boson of a global U(1) symmetry. Such Z_3 symmetric superpotential in the triplet extensions [6, 8] can also lead to the existence of similar light pseudoscalar. Existence of light boson(s) makes the triplet charged Higgs boson phenomenology further more interesting. In this article our main focus is to distinguish triplet-like extensions from the usual doublet-like extensions. We will consider an extension of MSSM with a SM gauge singlet and a $Y = 0$ triplet superfields, called the TNMSSM [12]. It gives the possibility to probe both the non-standard modes of the light charged Higgs boson decays, i.e. $h^{\pm} \to a_1 W^{\pm}$ and $h^{\pm} \to ZW^{\pm}$. The first one is possible due to existence of pNG boson and the second one is due to triplet structure of the light charged Higgs boson.

The triplet-type charged Higgs bosons are different from the doublet-type in two aspects. Firstly they do not couple directly to fermions with the usual Yukawa interaction and secondly they can decay into $ZW^{\pm}$. So far the searches of the light charged Higgs

boson at colliders, specially at the LHC, were focused on the doublet-like light charged Higgs [13–16]. The doublet-like charged Higgs boson is obtained through fermionic production modes, viz. $pp \to tbh^\pm/$, $gb \to t, h^\pm$, and then it is searched via $h^\pm \to \tau\nu/tb$. However, a triplet-like charged Higgs boson will be surely missed in this case, as it does not couple to fermions directly, which suppresses both the production and its fermionic decay modes. In a PYTHIA based analysis we try to distinguish such light doublet- and triplet-type charged Higgs bosons at the LHC.

We organize the paper as follows. In section 2 we give a brief summer of possible extensions of the Higgs sectors where the charged Higgs can come from different representations. Section 3 gives a summer of the triplet/singlet extension of the MSSM. Possible non-standard decays of the triplet-type charged Higgs bosons are discussed in section 4. In section 5 we treat the phenomenology of triplet- and doublet-like light charged Higgs boson and choose some benchmark points for a collider study at the LHC. In section 6 we perform a detail collider simulation for the signal and consider all the dominant SM backgrounds for the chosen final states, presenting the relative results. In section 7 we present the results for the reconstruction of the charged Higgs mass and in section 8 the correlation among various model with singly and doubly charged Higgs bosons before our conclusions, which are contained in section 9.

2 Charged Higgs bosons in various supersymmetric extensions of the SM

In the Standard Model we do not have any physical charged Higgs boson and this physical state can be achieved by extending the scalar sectors with at least one more $\mathrm{SU}(2)_L$ doublet or triplet. We summarize in this section the status of the charged Higgs sector in various models beyond the SM, comparing the number of the charged Higgs bosons and their most important features in terms of allowed decay modes. In table 1 we present the total Higgs spectrum along with the most important feature of the lightest charged Higgs boson in various supersymmetric extensions of the SM.

The MSSM is the most simple supersymmetric theory which allows a single charged Higgs boson in the spectrum. However the charged Higgs boson decays mostly in fermionic modes, viz. τ, ν and/or t, b. There is an inherent mass degeneracy (nearly) with the pseudoscalar boson (A) and heavy Higgs boson (H) present in the spectrum which prohibits the decays of $h^\pm \to A/HW^\pm$, as shown in scenario (a). In the simplest extension of MSSM, i.e. the NMSSM, the situation is similar, scenario (b). This is due to the fact that the singlet superfield, after acquiring vev, give rise to an additional scalar and pseudo-scalar in the spectrum but not to a charged Higgs boson. Instead of one, now there are two pseudoscalar bosons. Among which the doublet one will be degenerate with the charged Higgs boson and singlet one can be arbitrary. A very light pseudoscalar can be achieved by considering Z_3 symmetric superpotential (scenario (c)), which is realized in the limit $A_i \to 0$. In this limit there is an extra U(1) global symmetry, known as the R-symmetry in the literature [11], which is common to supersymmetric theories with only cubic terms in the superpotential (scale invariant). The lightest pseudoscalar of the spectrum is the Nambu-Goldstone mode of this extra symmetry, if $A_i \equiv 0$. If the symmetry is softly broken

MSSM (a)	NMSSM (b)	NMSSM + $A_i \sim 0$ (c)
$H^\pm$, A degenerate	$H^\pm$, a_1, a_2	$H^\pm \to a_1 W^\pm$ allowed
1 $H^\pm$		1 $H^\pm$
Triplet Superfield $\hat{T}$		
$Y = 0$ (d)	$Y = \pm 1$ (e)	$Y = 0, \pm 1$ (f)
$h_1^\pm \not\to a_1 W^\pm$ ($m_{a_1} \gtrsim m_{h_1^\pm}$)	$h_1^\pm \to ZW^\pm$ allowed	custodial symmetry
3 $h_i^\pm$	3 $h_i^\pm$, 2 $h_j^{\pm\pm}$	5 $h_i^\pm$, 2 $h_j^{\pm\pm}$
MSSM + $\hat{S}$ + $\hat{T}$ with Y = 0 + $A_i \sim 0$ (g)		
$h_1^\pm$ triplet-type		
$h_1^\pm \to ZW^\pm$ enhanced for $\lambda_T \sim 0$		
$h_1^\pm \to a_1 W^\pm$ allowed		
3 $h_i^\pm$		

Table 1. The charged Higgs sector in various SUSY theories.

the pseudoscalar takes the role of an axion-like particle. Having a very low mass the decay $H^\pm \to a_1 W^\pm$ is kinematically allowed, however such light pseudoscalar faces direct and indirect constraints from LEP [17, 18] and other experiments [19, 20].

Scenarios (d), (e) and (f) correspond to $Y = 0$, $Y = \pm 1$ and $Y = 0, \pm 1$ (Georgi-Machacek) cases where one or more $SU(2)_L$ triplet superfields are added to the MSSM superfield content. In the simplified extension of (d), where a $Y = 0$ triplet superfield is added to the MSSM, there are two more singly charged Higgs boson in the spectrum respect to the MSSM. The triplet charged Higgs bosons do not couple directly to the fermions, which makes their production at the LHC rather difficult, their decay to fermions is also suppressed and non-standard decays come into the picture [21, 22]. However, in this scenario the two-body decay $h_1^\pm \to a_1 W^\pm$ is not allowed because $m_{h_1^\pm} \lesssim m_{a_1}$ [21, 22]. The most important decay mode is then $h_1^\pm \to ZW^\pm$. This interaction is present at tree-level in theories with scalar triplets which acquire vevs and break custodial symmetry at the tree-level. Instead, if the model has scalar doublets or singlets of $SU(2)_L$ the breaking of the custodial symmetry is only possible at loop level and so is the decay $h_i^\pm \to ZW^\pm$. If the triplet superfield has $Y = \pm 1$ hypercharge, (scenario (e)), then in the spectrum, we will see a doubly charged Higgs bosons along with two additional triplet-type singly charged Higgs bosons [8]. Finally scenario (f) has both a $Y = 0$ and a $Y = \pm 1$ triplet superfields and the corresponding charged Higgs bosons. This is the supersymmetric version of the well-known Georgi-Machacek model [9]. The most important feature of scenario (f) is that the custodial symmetry can be naturally imposed [10].

Scenario (g) is considered in [23], where on the top of the MSSM superfield content, there is a singlet superfield and a triplet superfield with $Y = 0$. The superpotential is Z_3 symmetric, meaning that only cubic terms are allowed. In the limit $A_i \sim 0$, it exhibits a softly broken U(1) symmetry, similarly to scenario (c) and the lightest pseudoscalar is

the pseudo Nambu-Goldstone mode of this extra U(1) symmetry that can be very light. In this scenario the lightest charged Higgs boson can decay in $a_1 W^\pm$ and $Z W^\pm$ and if it is triplet-like its decay into fermions is suppressed. Below we briefly introduce the model which will be used later for the phenomenological studies to distinguish among doublet and triplet charged Higgs boson(s) at the LHC.

3 The model

We consider an extension of the MSSM with a (gauge) singlet superfield $\hat{S}$ and a triplet superfield $\hat{T}$ with $Y = 0$. The model is detailed in [12] and here we will give the very basic properties. The Higgs superfields are given below,

$$\hat{T} = \begin{pmatrix} \sqrt{\frac{1}{2}}\hat{T}^0 & \hat{T}_2^+ \\ \hat{T}_1^- & -\sqrt{\frac{1}{2}}\hat{T}^0 \end{pmatrix}, \qquad \hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix}, \qquad \hat{H}_d = \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix}, \qquad \hat{S}, \qquad (3.1)$$

where $\hat{T}^0$ is a complex neutral superfield, while $\hat{T}_1^-$ and $\hat{T}_2^+$ are the charged Higgs super-fields. $\hat{H}_u$ and $\hat{H}_d$ are the usual doublet superfields of the MSSM and $\hat{S}$ is the singlet superfield. The gauge symmetry implies that the Yukawa interactions are identical to the MSSM ones, because neither the singlet nor the triplet superfields have any interaction with the fermionic superfields. This means that the superpotential can be written as

$$\hat{W}_{\text{TNMSSM}} = \hat{W}_{\text{MSSM}} + \hat{W}_{TS}, \qquad (3.2)$$

with

$$\hat{W}_{\text{MSSM}} = y_t \hat{U}\hat{H}_u \cdot \hat{Q} - y_b \hat{D}\hat{H}_d \cdot \hat{Q} - y_\tau \hat{E}\hat{H}_d \cdot \hat{L}, \qquad (3.3)$$

being the superpotential of the MSSM, while

$$\hat{W}_{TS} = \lambda_T \hat{H}_d \cdot \hat{T}\hat{H}_u + \lambda_S \hat{S}\hat{H}_d \cdot \hat{H}_u + \frac{\kappa}{3}\hat{S}^3 + \lambda_{TS}\hat{S}\text{Tr}[\hat{T}^2] \qquad (3.4)$$

Here "·" denotes a contraction with the Levi-Civita symbol ϵ^{ij}, with $\epsilon^{12} = +1$.

It is a characteristic of any scale invariant supersymmetric theory with a cubic superpo-tential that the complete Lagrangian with the soft SUSY breaking terms has an accidental Z_3 symmetry. This is generated by the invariance of all of its components after multipli-cation of the chiral superfields by the phase $e^{2\pi i/3}$. This Z_3 symmetry is promoted to a global U(1) symmetry in the limit $A_i \to 0$, where the A_i are the trilinear terms of the soft-breaking part of the scalar potential [12]. This global U(1) symmetry can be softly broken by small A_i, giving rise to a very light pseudoscalar which is the pseudo Nambu-Goldstone mode of the symmetry.

We assume that all the coefficients involved in the Higgs sector are real in order to preserve CP invariance. The breaking of the $\text{SU}(2)_L \times \text{U}(1)_Y$ electroweak symmetry is then obtained by giving real vevs to the neutral components of the Higgs field

$$< H_u^0 > = \frac{v_u}{\sqrt{2}}, \quad < H_d^0 > = \frac{v_d}{\sqrt{2}}, \quad < S > = \frac{v_S}{\sqrt{2}}, \quad < T^0 > = \frac{v_T}{\sqrt{2}}, \qquad (3.5)$$

which give mass to the $W^\pm$ and Z bosons

$$m_W^2 = \frac{1}{4}g_L^2(v^2 + 4v_T^2), \quad m_Z^2 = \frac{1}{4}(g_L^2 + g_Y^2)v^2, \quad v^2 = (v_u^2 + v_d^2), \quad \tan\beta = \frac{v_u}{v_d}, \quad (3.6)$$

and also induce, as mentioned above, a μ-term of the form $\mu_D = \frac{\lambda_S}{\sqrt{2}}v_S + \frac{\lambda_T}{2}v_T$. The triplet vev v_T is strongly constrained by the global fit on the measurement of the ρ parameter [7]

$$\rho = 1.0004^{+0.0003}_{-0.0004}, \quad (3.7)$$

which restricts its value to $v_T \leq 5\,\text{GeV}$. Respect to the tree-level expression, the non-zero triplet contribution to the $W^\pm$ mass leads to a deviation of the ρ parameter

$$\rho = 1 + 4\frac{v_T^2}{v^2}. \quad (3.8)$$

4 Triplet-like singly charged Higgs bosons

The lightest triplet-like charged Higgs in TNMSSM [12, 23, 24] can decay to $ZW^\pm$ as well as to $a_1W^\pm$. Establishing these two non-standard decay modes will be sufficient to prove the existence of higher representations $\text{SU}(2)_L$ in the Higgs spectrum, i.e. the triplet as well as the SM gauge singlet. As we already point out in section 2 that in the case of a triplet with non-zero hypercharge, there is a doubly-charged Higgs boson in the spectrum. Its phenomenology have been studied extensively in the literature [25–28]. In this article our goal is to distinguish between doublet- and triplet-like charged Higgs boson by searching for singly charged Higgs bosons at the LHC in appropriate decay channels.

The phenomenology of the lightest charged Higgs boson of the TNMSSM is affected by the presence of a light pseudoscalar, which induces a new decay mode $h_1^\pm \to a_1W^\pm$. Along with the existence of the light pseudoscalar, the triplet-like charged Higgs boson adds another tree-level decay mode $h_1^\pm \to ZW^\pm$, which is not possible otherwise. In particular, a $Y = 0$ triplet-like charged Higgs boson can decay into $ZW^\pm$, which is a signature of custodial symmetry breaking. If the model has only doublets of $\text{SU}(2)_L$ then the decay $h^\pm \to ZW^\pm$ is loop-induced only. Apart from that, the usual doublet-like decay modes into $\tau\nu$ and tb are present via the mixing with the doublets. We summarize the different possible decay modes in the following paragraphs.

The trilinear couplings with charged Higgs bosons, scalar (pseudoscalar) Higgs bosons and $W^\pm$ are given by

$$g_{h_i^\pm W^\mp h_j} = \frac{i}{2}g_L\left(\mathcal{R}_{j2}^S\mathcal{R}_{i3}^C - \mathcal{R}_{j1}^S\mathcal{R}_{i1}^C + \sqrt{2}\mathcal{R}_{j4}^S\left(\mathcal{R}_{i2}^C + \mathcal{R}_{i4}^C\right)\right), \quad (4.1)$$

$$g_{h_i^\pm W^\mp a_j} = \frac{g_L}{2}\left(\mathcal{R}_{j1}^P\mathcal{R}_{i1}^C + \mathcal{R}_{j2}^P\mathcal{R}_{i3}^C + \sqrt{2}\mathcal{R}_{j4}^P\left(\mathcal{R}_{i2}^C - \mathcal{R}_{i4}^C\right)\right), \quad (4.2)$$

where $\mathcal{R}^S, \mathcal{R}^P, \mathcal{R}^C$ are the mixing matrix corresponding to scalar, pseudoscalar and charged Higgs bosons respectively, with $\mathcal{R}_{j4}^S, \mathcal{R}_{j4}^P, \mathcal{R}_{j,2}^C, \mathcal{R}_{j4}^C$ being the triplet part of the mixing matrices [23].

Both the triplet and doublet have $\text{SU}(2)_L$ charge and hence they couple to $W^\pm$ boson. However the $W^\pm$ boson is in the triplet representation of $\text{SU}(2)_L$ and this means that in

the $W^\pm h_i h_j^\mp$ coupling the neutral and charged Higgs bosons have to be doublet(triplet) and triplet-(doublet-)type respectively in order to maintain the gauge invariance.

The decay width of a massive charged Higgs boson in a W boson and a scalar (or pseudoscalar) boson is given by

$$\Gamma_{h_i^\pm \to W^\pm h_j/a_j} = \frac{G_F}{8\sqrt{2}\pi} m_{W^\pm}^2 |g_{h_i^\pm W^\mp h_j/a_j}|^2 \sqrt{\lambda(1, x_W, x_{h_j/a_j})} \, \lambda(1, y_{h_i^\pm}, y_{h_j/a_j}), \quad (4.3)$$

where $x_{W,h_j} = \frac{m_{W,h_j}^2}{m_{h_i^\pm}^2}$ and $y_{h_i^\pm,h_j} = \frac{m_{h_i^\pm,h_j}^2}{m_{W^\pm}^2}$ and similarly for a_j. In TNMSSM this decay channel is prominent for a light charged Higgs boson and it is the dominant decay mode if the charged Higgs boson is triplet-like, because of the suppression of the fermionic couplings.

In theories with $Y = 0, \pm 2$ hypercharge triplets, which generally break the custodial symmetry, there is a tree-level interactions $h_i^\pm - W^\mp - Z$ [4]. In the TNMSSM this coupling is given by

$$g_{h_i^\pm W^\mp Z} = -\frac{i}{2} \left(g_L \, g_Y \left(v_u \sin\beta \, \mathcal{R}_{i1}^C - v_d \cos\beta \, \mathcal{R}_{i3}^C \right) + \sqrt{2} \, g_L^2 v_T \left(\mathcal{R}_{i2}^C + \mathcal{R}_{i4}^C \right) \right), \quad (4.4)$$

where the explicit definition of the rotation angles can be found in [23]. The on-shell decay width is given by

$$\Gamma_{h_i^\pm \to W^\pm Z} = \frac{G_F \cos^2\theta_W}{8\sqrt{2}\pi} m_{h_i^\pm}^3 |g_{h_i^\pm W^\mp Z}|^2 \sqrt{\lambda(1, x_W, x_Z)} \left(8 \, x_W \, x_Z + (1 - x_W - x_Z)^2 \right), \quad (4.5)$$

where $\lambda(x, y, z) = (x - y - z)^2 - 4 \, y \, z$ and $x_{Z,W} = \frac{m_{Z,W}^2}{m_{h_i^\pm}^2}$ [29]. As it is extensively explained in [23], this decay channel is enhanced for a triplet-like charged Higgs boson in the limit $\lambda_T \sim 0$ due to the same sign values of $\mathcal{R}_{12}^C$ and $\mathcal{R}_{14}^C$.

Beside the non-zero $h_i^\pm - W^\mp - Z$ coupling at the tree-level due to custodial symmetry breaking, the charged Higgs bosons can also decay into fermions through the Yukawa interaction given below

$$g_{h_i^+ \bar{u} d} = i \left(y_u \, \mathcal{R}_{i1}^C \, \mathsf{P_L} + y_d \, \mathcal{R}_{i3}^C \, \mathsf{P_R} \right), \quad (4.6)$$

governed by doublet part of the charged Higgses. The decay width at leading order is

$$\Gamma_{h_i^\pm \to u \, d} = \frac{3}{4} \frac{G_F}{\sqrt{2}\pi} m_{h_i^\pm} \sqrt{\lambda(1, x_u, x_d)} \Bigg[(1 - x_u - x_d) \left(\frac{m_u^2}{\sin^2\beta} (\mathcal{R}_{i1}^C)^2 + \frac{m_d^2}{\cos^2\beta} (\mathcal{R}_{i3}^C)^2 \right) \\ - 4 \frac{m_u^2 m_d^2}{m_{h_i^\pm}^2} \frac{\mathcal{R}_{i1}^C \mathcal{R}_{i3}^C}{\sin\beta \cos\beta} \Bigg], \quad (4.7)$$

where $x_{u,d} = \frac{m_{u,d}^2}{m_{h_i^\pm}^2}$. The decay of the charged Higgs bosons into quarks is suppressed in the case of triplet-like eigenstates, where $\mathcal{R}_{i1,i3}^C \ll 1$.

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5 Benchmark points for the collider study

In this section we select four benchmark points to perform the collider study and to distinguish doublet- and triplet-like points at the LHC. It is evident from eq. (3.4) that the triplet states do not couple to the fermions, which makes their production at the LHC or earlier colliders very difficult as essentially all of them are fermionic colliders. Triplet does not have any SU(3) charge, thus normal gluon fusion at the LHC cannot produce it. The same property explains why their decays in fermionic modes or fermion induced modes ($\gamma\gamma$, gg) are also suppressed. In [24] we considered the most relevant experimental bounds to find out the allowed parameter regions. From table 2 we can see apart from the $\sim 125\,\text{GeV}$ Higgs boson the next heavier states are mostly triplets and also for all the benchmark points there is a mostly singlet like pseudoscalar, which affects their branching fraction by generating new modes $h_i \to a_1 a_1$ (for neutral Higgs bosons) and $h_i^\pm \to a_1 W^\pm$ (for charged Higgs bosons). This implies that probing the heavier states will require either searches in new final states and/or higher luminosities.

In table 2 we show the mass spectrum of the selected benchmark points. Together with the recent Higgs data, we have also considered the recent bounds on the stop and sbottom masses [37, 38] and the mass bounds on the lightest chargino from LEP [39]. The recent bounds on the charged Higgs boson mass from both CMS [40, 41] and ATLAS [42, 43] are also taken into account. These bounds have been derived in their searches for the light charged Higgs bosons from the decay of a top quark and/or via charged Higgs production in pairs/association, and its decays to $\tau\bar{\nu}$. Addition of any new decay mode will further lower the lower bound for the charged mass exclusion.

The branching fractions of the SM-like Higgs boson for the four benchmark points are presented in table 3. They are consistent with the observed branching fraction at 2σ level. The decay channels of the light pseudoscalar a_1 are presented in table 4. Even though they are mostly singlet like, they decay to fermions via mixing with the doublets. The benchmark points are chosen with different dominant decay modes of the charged Higgs bosons. The mostly triplet-like charged Higgs would dominantly decays into $ZW^\pm$. Similarly for some points it can decay to $a_1 W^\pm$ and for mostly doublet-like charged Higgs boson it decays to $t\,b$.

In table 5 presents the two-body decay branching fractions of the charged Higgs for the benchmark points. We can see that for BP1, the decay branching fraction to $a_1 W^\pm$ is the highest. BP2 seems to have decent decay rates into $h_{125}W^\pm$, $ZW^\pm$ and into tb making it a mixed point where both doublet and triplet natures manifest. In contrary to BP1, BP3 is a doublet-like points which mostly decays to tb. Finally, BP4 is characterized by a single dominant decay channel, $h_1^\pm \to Z\,W^\pm$ with a branching fraction of 0.994. We will see later in the section how we can distinguish such doublet- and triplet-like points. The color code used in table 2 is green to represent a triplet-like charged Higgs boson and red for the doublet-like. We see that for BP3 the charged Higgs boson is mostly doublet and so it is in red. Similarly blue color has been used to signify singlet-like light pseudoscalar boson.

Figure 1 describes a correlation plot for $\mathcal{Br}(h_1^\pm \to a_1 W^\pm)$ and $\mathcal{Br}(h_1^\pm \to ZW^\pm)$ for the light charged Higgs boson ($h_1^\pm$). The red points are doublet-like charged Higgs, the green

Benchmark Points	BP1	BP2	BP3	BP4
m_{h_1}	~ 125	~ 125	~ 125	~ 125
m_{h_2}	316.14	340.44	272.87	174.21
m_{h_3}	522.41	382.56	358.12	1027.3
m_{h_4}	673.45	514.16	2094.4	1547.7
m_{a_1}	41.221	36.145	30.655	61.537
m_{a_2}	181.34	428.68	278.22	1052.7
m_{a_3}	559.32	519.01	2149.4	1325.9
$m_{h_1^\pm}$	179.69	339.97	289.51	174.11
$m_{h_2^\pm}$	316.20	399.84	2089.7	1032.9
$m_{h_3^\pm}$	535.21	519.02	2144.9	1325.9

Table 2. Benchmark points for a collider study consistent with the $\sim 125\,$GeV Higgs mass, where the $h_{i=1,2,3,4}$, $a_{i=1,2,3}$ are at one-loop and $h_{i=1,2,3}^\pm$ masses are calculated at tree level. We color in red the states which are mostly doublets ($> 90\%$) and in blue and green those which are mostly singlet and triplet ($> 90\%$) respectively. The points are consistent with the 2σ limits of $h_{125} \to WW^*, ZZ^*, \gamma\gamma$ [30–36].

Benchmark Points	Branching ratios			
	$a_1 a_1$	$W^\pm W^\mp$	ZZ	$b\bar{b}$
BP1	0.105	0.148	0.020	0.686
BP2	0.045	0.143	0.019	0.748
BP3	0.052	0.115	0.015	0.770
BP4	0.057	0.129	0.017	0.752

Table 3. Relevant decay branching ratios of h_{125} for the benchmark points.

Benchmark Points	Branching ratios(%)		
	$b\bar{b}$	$\tau\bar{\tau}$	$\mu\bar{\mu}$
BP1	0.942	5.77×10^{-2}	2.06×10^{-4}
BP2	0.942	5.80×10^{-2}	2.07×10^{-4}
BP3	0.941	5.85×10^{-2}	2.09×10^{-4}
BP4	0.943	5.72×10^{-2}	2.03×10^{-4}

Table 4. Decay branching ratios of a_1 for the benchmark points BP_i. The kinematically forbidden decays are marked with dashes.

Benchmark	Branching ratios					
Points	$a_1 W^\pm$	$h_{125} W^\pm$	$Z W^\pm$	$t b$	$\tau \nu_\tau$	$\mu \nu_\mu$
BP1	0.969	5.56×10^{-5}	2.09×10^{-2}	9.58×10^{-3}	1.29×10^{-4}	4.57×10^{-7}
BP2	3.01×10^{-2}	0.213	0.236	0.520	8.87×10^{-5}	3.15×10^{-7}
BP3	6.43×10^{-2}	3.51×10^{-3}	1.94×10^{-10}	0.932	9.25×10^{-5}	3.28×10^{-7}
BP4	1.03×10^{-5}	3.34×10^{-3}	0.994	–	1.60×10^{-3}	5.68×10^{-6}

Table 5. Decay branching ratios of $h_1^\pm$ for the benchmark points. The kinematically forbidden decays are marked with a dash.

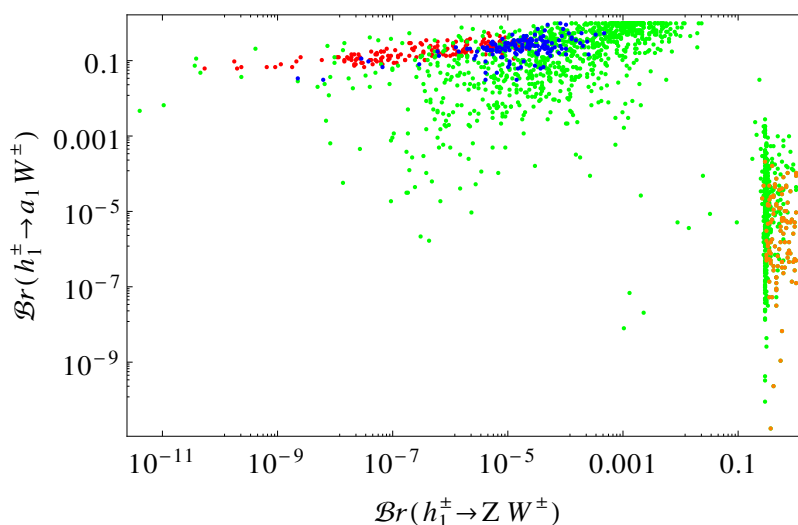**Figure 1.** Correlation plot of the branching ratios for the non-standard decays $h_1^\pm \to Z W^\pm$ and $h_1^\pm \to a_1 W^\pm$. The red points are doublet-like charged Higgs, the green ones are triplet-like and the blue ones are mixed-one. The orange ones are characterized by $\lambda_T \sim 0$ [23]. We can see that these two decay channels are almost mutually excluded.

ones are triplet-like and the blue ones are mixed-one. The orange ones are characterized by $\lambda_T \sim 0$ [23]. We can see that $h_1^\pm \to a_1 W^\pm$ and $h_1^\pm \to ZW^\pm$ decay channels are almost mutually excluded and it would be very difficult to probe both the triplet nature of the charged Higgs boson as well as the existence of the light pseudoscalar a_1 for the same benchmark point.

We have calculated the light charged Higgs production cross-sections in pairs and in association of other particles at the LHC for these benchmark points. For this purpose we have implemented the model in SARAH [44] and we have generated the model files for CalcHEP [45]. The cross-sections have been calculated at the tree-level via Calchep_3.6.23 [45] and table 6 presents the cross-sections which include the associated K-factors [46, 47]. We can see that for BP1, $h_1^\pm$ is degenerate with a_2, and for BP2 and BP4, $h_1^\pm$ is degenerate with h_2 (see table 2). The cross-section contributions from such associated charged Higgs production processes are the dominant ones for the respective benchmark points.

	Cross section in fb			
	BP1	BP2	BP3	BP4
$h_1^\pm h_1^\mp$	148.00	13.00	12.48	166.50
$h_{125} h_1^\pm$	6.93×10^{-4}	1.82×10^{-2}	0.35	0.15
$a_1 h_1^\pm$	2.14×10^{-2}	2.48×10^{-3}	5.12	9.68×10^{-7}
$h_2 h_1^\pm$	0.28	26.42	13.89	334.62
$a_2 h_1^\pm$	292.45	2.38×10^{-3}	12.54	7.07×10^{-8}
$Z h_1^\pm$	1.44×10^{-3}	3.08×10^{-2}	2.66×10^{-8}	0.33
$W^\mp h_1^\pm$	2.08×10^{-2}	0.17	166.21	0.88
$t h_1^\pm$	8.13×10^{-2}	3.50	4.48×10^3	7.60
$tb h_1^\pm$	3.28×10^{-2}	0.21	386.32	3.81

Table 6. Production cross-section of the charged Higgs boson $h_1^\pm$ in various channels at the LHC for a center of mass energy of 14 TeV for the three benchmark points. A K-factor of 1.6 has been used.

6 Final state topologies and simulation at the LHC

The TNMSSM can have a light pseudoscalar a_1 with $m_{a_1} \lesssim 60$ GeV (see table 2). The existence of such light pseudoscalar opens a new mode in the decay of the light charged Higgs boson, i.e. $h_1^\pm \to a_1 W^\pm$, and the light pseudoscalar boson can further decay into τ or b pairs. The other possible signature comes from the triplet nature of the light charged Higgs boson, which prompts the $h_1^\pm \to Z W^\pm$ decay. For the chosen benchmark points we will focus on these non-standard decays of the charged Higgs boson, which is the result of the existence of a singlet and triplet scalar in the spectrum. For this purpose CalcHEP [45] has been used to generate the decay file SLHA, containing the decay branching ratios and the corresponding mass spectra. The generated events have then been simulated with PYTHIA [48] via the SLHA interface [49, 50]. The simulation at hadronic level has been performed using the Fastjet-3.0.3 [51] with the CAMBRIDGE AACHEN algorithm. We have selected a jet size $R = 0.5$ for the jet formation, with the following criteria:

- the calorimeter coverage is $|\eta| < 4.5$,

- the minimum transverse momentum of the jet $p_{T,\text{min}}^{\text{jet}} = 10$ GeV and jets are ordered in p_T,

- leptons ($\ell = $ e, μ) are selected with $p_T \geq 10$ GeV and $|\eta| \leq 2.5$,

- no jet should be accompanied by a hard lepton in the event,

- $\Delta R_{lj} \geq 0.4$ and $\Delta R_{ll} \geq 0.2$,

- Since an efficient identification of the leptons is crucial for our study, we additionally require a hadronic activity within a cone of $\Delta R = 0.3$ between two isolated leptons to be $\leq 0.15 \, p_T^\ell$ GeV, with p_T^ℓ the transverse momentum of the lepton, in the specified cone.
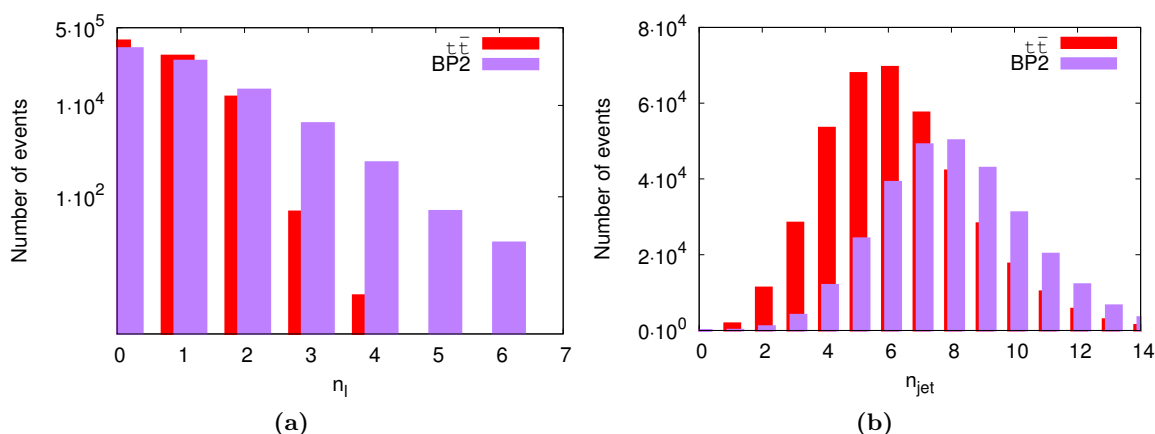
Figure 2. Jet and lepton multiplicity distributions from BP2 of the $h_1^\pm h_1^\mp$ signal and the SM background $t\bar{t}$ are shown in (a) and (b) respectively.
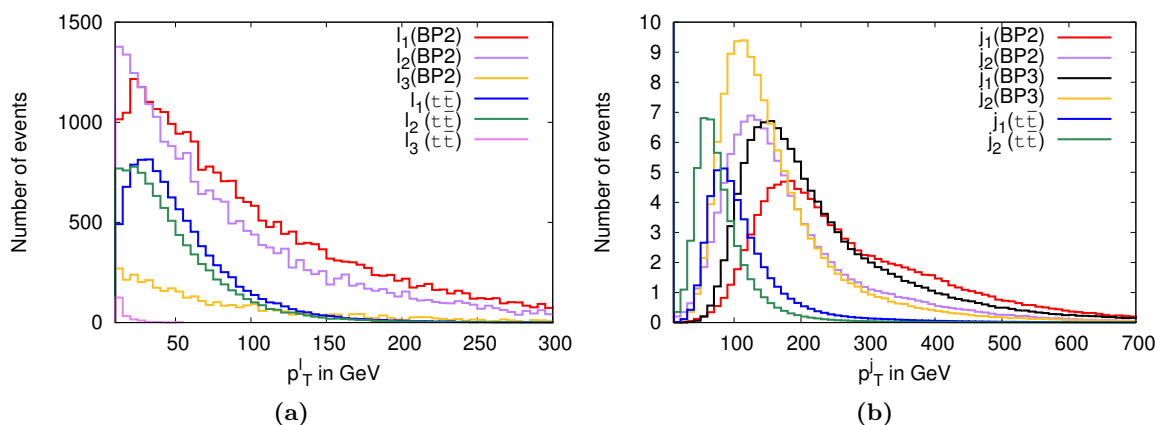

Figure 3. Lepton and Jet p_T distributions coming from BP2 of the $h_1^\pm h_1^\mp$ signal and the SM background $t\bar{t}$ are shown in (a) and (b) respectively.

The non-standard decay products of the light charged Higgs boson $h_1^\pm$ give rise to gauge bosons $Z, W^\pm$ which further decay into charged leptons. Here we tag e, μ as charged leptons only and τ is tagged as jet via its hadronic decay. Figure 2 (a) describes the lepton multiplicity distribution coming from BP2 of the $h_1^\pm h_1^\mp$ signal and the SM background $t\bar{t}$. Clearly a higher lepton multiplicity is a winner here. Similarly figure 2 (b) shows the jet multiplicity distributions from BP2 of the $h_1^\pm h_1^\mp$ signal and the SM background $t\bar{t}$. Concerning the signal, these jets are coming from the hadronic decay of $Z, W^\pm, \tau$ as well as the b-jets coming from $h_1^\pm$. Similarly to the lepton multiplicity, here also we see that the higher jet-multiplicity is preferred for the signal, which can be used to suppress the SM backgrounds.

We keep the cuts in p_T of the leptons and the jets relatively low ($p_T \geq 10\,\text{GeV}$), because they will be generated from the lightest pseudoscalar decays. Figure 3 (a) shows the lepton p_T distributions for the three leptons in their kinematical order coming from the
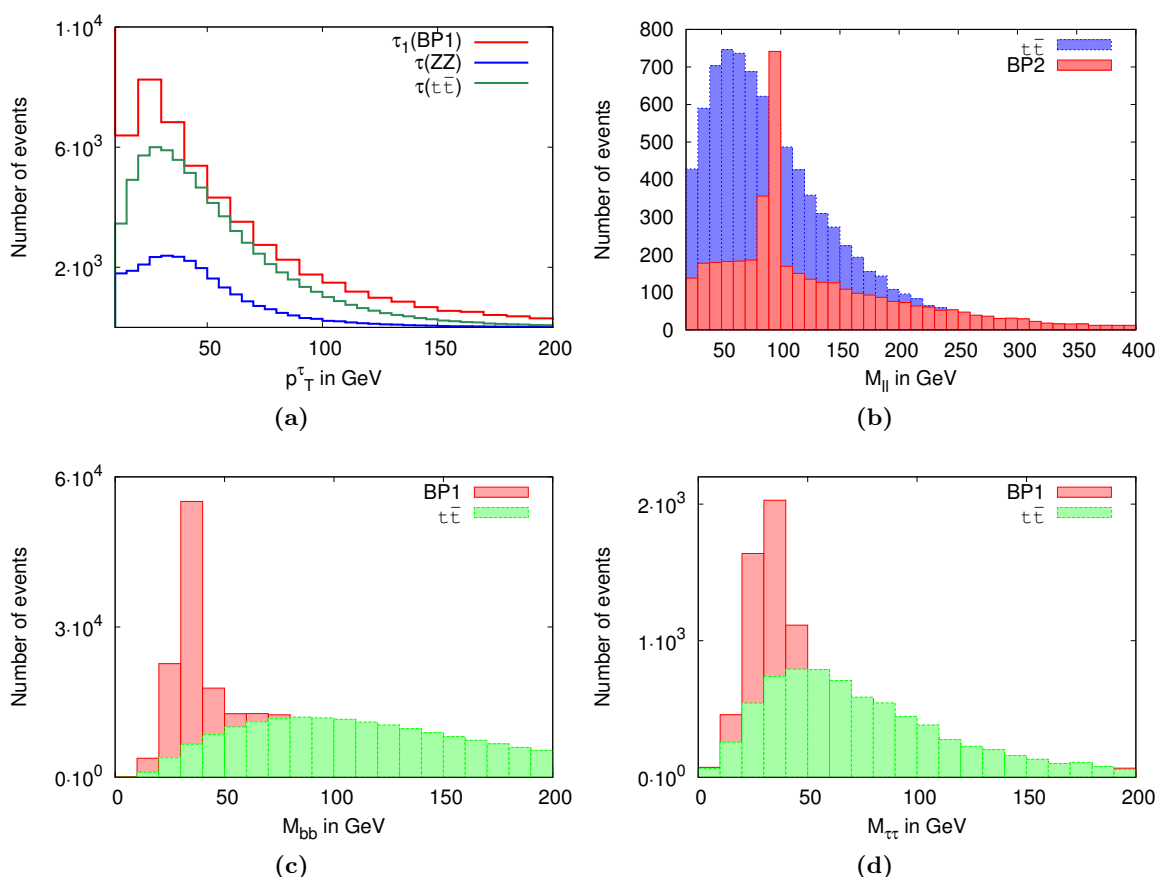
Figure 4. τ-p_T distributions for $h_1^{\pm} h_1^{\mp}$ signal of BP1, ZZ and $t\bar{t}$ are shown in (a). Invariant mass distribution for the (b) di-lepton, (c) di-b-jets, and (d) di-tau coming from BP2 of the $h_1^{\pm} h_1^{\mp}$ signal, the SM background $t\bar{t}$ and from BP1 of the $h_1^{\pm} h_1^{\mp}$ signal, the SM background $t\bar{t}$ respectively.

signal $h_1^{\pm} h_1^{\mp}$ for BP2 and from the $t\bar{t}$. The leptons coming from the signals are of high p_T because they come from a rather heavy charged Higgs boson for BP2 ($m_{h_1^{\pm}} \sim 340 \, \text{GeV}$), compared to those coming from top quarks. The third lepton coming from the $t\bar{b}$ generally arises from the semi-leptonic b decays and it is rather soft as can be seen from figure 3 (a).

Figure 3 (b) describes the jet p_T distributions for the first two p_T ordered jets coming from BP2 and BP3 of the $h_1^{\pm} h_1^{\mp}$ signal and the SM background $t\bar{t}$. We clearly see that a cut $p_T > 100 \, \text{GeV}$ on the first jet can reduce such backgrounds considerably. The tagging efficiency of the jet of the b-quark (b_{jet}) is obtained through the determination of the secondary vertex and it is therefore momentum dependent. For this purpose we have taken — for the b_{jet}'s from $t\bar{t}$ — the single-jet tagging efficiency equal to 0.5, while for the remaining components of the final state we have followed closely the treatment of [52]. Here, in the case of the τ_{jet} we have considered the hadronic decay of the τ to be characterized by at least one charged track with $\Delta R \leq 0.1$ of the candidate τ_{jet} [53, 54]. Figure 4 (a) shows the τ_{jet} p_T distributions for the BP1 and the dominant SM backgrounds coming from ZZ, $t\bar{t}$.

Figure [4](b) describes the invariant mass distribution for the di-lepton coming from BP2 of the $h_1^\pm h_1^\mp$ signal and the SM background $t\bar{t}$. It can be seen that in the case of $t\bar{t}$ both the charged leptons are coming from the corresponding $W^\pm$ decays and hence the invariant mass distribution of lepton pair does not have any peak. However, because the charged Higgs boson decays to $Z, W^\pm$, we see the Z mass peak in the invariant mass distribution. The situation is more interesting in the case where a_1 comes from the charged Higgs decay $h_1^\pm \to a_1 W^\pm$ and then further decays into b or τ pairs. In this scenario the peak around m_{a_1} is easily visible in the variant mass distribution of the di-b-jets and τ-jet pair for BP1, as shown in figure [4](c) and figure [4](d) respectively. This happens due to the fact that for BP1 $\mathcal{B}r(h_1^\pm \to a_1 W^\pm \sim 97\%)$ (see table [5]). We will extract these peaks later to probe such light pseudoscalar.

In oder to distinguish the doublet- and triplet-type of charged Higgs boson we have to find final states with very different predictions for the number of events for the four benchmark points. We shall see in the coming subsections that describes different final states, that it is possible to discriminate between the non-standard decay modes of the charged Higgs boson, i.e. $h_1^\pm \to a_1 W^\pm$ and $h_1^\pm \to ZW^\pm$.

6.1 $2b + 2\tau$

In BP1, BP2 and BP4, the non-standard decay modes i.e. $a_1 W^\pm$ and $ZW^\pm$ of the light charged Higgs bosons are open. This results into the possibility to have τ and b pairs either from a_1 or Z boson. In this subsection we focus our attention on the final state involving $2b + 2\tau$. For BP1 the branching ratio into $a_1 W^\pm$ is very high, $\mathcal{B}r(h_1^\pm \to a_1 W^\pm \sim 97\%)$ and thus the possibility of having two a_1 in the final state is also very high. Such a_1, produced from the charged Higgs boson decay, mostly decays to b pair ($\sim 95\%$) but also goes to τ pairs ($\sim 5\%$), cf. table [4]. Thus $2b + 2\tau$ is the suitable final state to look for. A scenario like BP1 can be easily probed via this final state where the existence of light pseudoscalar can be also explored.

Table [7] gives the final state numbers with the cumulative cuts for the benchmark points as well as for the dominant SM backgrounds. For the signal, we have included the dominant contributions coming from $h_1^\pm h_1^\mp$, $h_2 h_1^\pm$ and $a_2 h_1^\pm$, whose cross-sections can be found in table [6]. There are many SM processes with final states involving b coming from top quark or Z boson decays and τ coming from gauge bosons. The dominant SM backgrounds considered are $t\bar{t}$, $t\bar{t}V$, tZW, VV and VVV, where V corresponds to Z and/or $W^\pm$ bosons. A closer look to the final states will tell us that there are $W^\pm$ and Z bosons coming from the charged Higgs and neutral Higgs bosons which can provide additional jets and leptons in the final states. If we tag one of those $W^\pm$ boson via $m_{jj} \sim m_W$ with an additional charged lepton (e or μ), then mostly the $h_1^\pm h_1^\mp$ signal will be filtered over the background. In that case the signal significance for BP1 jumped to 7.6σ and such signal can be discovered with an integrated luminosity of $43\,\mathrm{fb}^{-1}$ at 5σ significance. However BP2, BP3 and BP4 will require a much higher integrated luminosity to prove this final state, i.e. 3718, 253 and much more than $3000\,\mathrm{fb}^{-1}$ respectively. Thus the considered final state can be very effective in the search of the $h_1^\pm \to a_1 W^\pm$ decay mode, which can potentially discover a light pseudoscalar boson.

Final states		Benchmark Points				Backgrounds			
		BP1	BP2	BP3	BP4	$t\bar{t}$	$t\bar{t}V$	$tZW^\pm$	VV/VVV
$2b+2\tau$	$h_1^\pm h_1^\mp$	52.00	4.51	2.71	2.44				
	$h_2 h_1^\pm$	0.48	21.75	12.84	10.60				
	$a_2 h_1^\pm$	406.99	0.00	43.57	0.00	24834.00	228.14	11.92	590.91
	$th_1^\pm$	0.00	0.00	620.45	0.85				
	$tbh_1^\pm$	0.00	0.00	25.84	0.00				
$+1\ell + m_{\mathrm{jj}} \sim m_W$	$h_1^\pm h_1^\mp$	10.75	1.02	0.25	0.50				
	$h_2 h_1^\pm$	0.11	3.72	2.21	1.34				
	$a_2 h_1^\pm$	67.34	0.00	8.98	0.00	0.00	25.36	2.91	0.20
	$th_1^\pm$	0.00	0.00	7.49	0.18				
	$tbh_1^\pm$	0.00	0.00	3.47	0.00				
Significance		7.60σ	0.82σ	3.14σ	0.37σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		43	3718	253	$\gg 3000$				

Table 7. The number of events for a $2b+2\tau$ final state at $100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC with $14\,\mathrm{TeV}$ center of mass energy.

6.2 3ℓ

The dominant modes for a triplet-type charged Higgs boson with an existent light pseudoscalar is either $a_1 W^\pm$ or $ZW^\pm$. The final states are, thus, rich in leptons, prompting the multi-leptonic channels. Along with the leptonic final states, there will be b-jets coming from the neutral Higgs bosons (a_1, a_2, h_2) and Z boson decays. Tagging with two such b-jets will help to control the SM backgrounds. However, due to the small production cross-sections of such triplet-like charged Higgs bosons, it is possible to probe such final states only at the LHC only with higher integrated luminosity.

In table 8 we present the number of events for the benchmark points and the dominant SM backgrounds with two different kind of selections for the 3ℓ final states at $100\,\mathrm{fb}^{-1}$ of integrated luminosities at the LHC with $14\,\mathrm{TeV}$ center of mass energy. In particular ( )† means $p_T^{\ell_2} \geq 30\,\mathrm{GeV} + p_T^{\ell_3} \geq 40\,\mathrm{GeV}$ whereas ( )* states that no p_T cuts are added. To reduce the background we consider the final state $(> 3\ell + > 2j + m_{\ell\ell} \sim m_Z)^\dagger$ and only BP4 can be probed earliest at the LHC, with an integrated luminosity of $437\,\mathrm{fb}^{-1}$. The other benchmark points will require a very high luminosity to probe the final state. However, tagging two b-jets by choosing $(> 3\ell + > 2b_{\mathrm{j}})^*$ final state BP1 and BP3 can be probed with much earlier data of 567 and $626\,\mathrm{fb}^{-1}$ of integrated luminosity. On the other hand, BP2 and BP4 demand 4216 and $3740\,\mathrm{fb}^{-1}$ of integrated luminosities respectively, which are on the edge of the HL-LHC project [55]. Finally, we tag the jet pair coming from the $W^\pm$ boson decays by choosing $(> 3\ell + m_{\mathrm{jj}} \sim m_W)^*$ final state. In this case the signal number improves a lot for BP4 and it can probed with very early data of $153\,\mathrm{fb}^{-1}$ integrated luminosity at the LHC with ECM of $14\,\mathrm{TeV}$.

In table 9 we present the case where we tag a tau-jet along with the $\geq 3\ell$ final states. This makes BP1 and BP4 probable with much earlier data, precisely with 48 and $54\,\mathrm{fb}^{-1}$

Final states		Benchmark Points				Backgrounds			
		BP1	BP2	BP3	BP4	$t\bar{t}$	$t\bar{t}V$	$tZW^{\pm}$	VV/VVV
$(>3\ell)^{\dagger}$	$h_1^{\pm}h_1^{\mp}$	6.56	8.48	0.06	31.41	0.00	348.69	68.14	4355.69
	$h_2 h_1^{\pm}$	0.02	21.35	5.80	171.21				
	$a_2 h_1^{\pm}$	14.64	0.00	2.96	0.00				
	$th_1^{\pm}$	0.00	0.00	3.00	2.78				
	$tbh_1^{\pm}$	0.00	0.00	1.16	0.00				
$(+>2\mathrm{j})^{\dagger}$	$h_1^{\pm}h_1^{\mp}$	6.07	8.32	0.06	30.08	0.00	329.52	62.32	2835.27
	$h_2 h_1^{\pm}$	0.03	20.64	5.76	162.07				
	$a_2 h_1^{\pm}$	14.64	0.00	2.96	0.00				
	$th_1^{\pm}$	0.00	0.00	3.00	2.66				
	$tbh_1^{\pm}$	0.00	0.00	1.16	0.00				
$(+m_{\ell\ell} \sim m_Z)^{\dagger}$	$h_1^{\pm}h_1^{\mp}$	3.11	5.73	0.01	24.14	0.00	236.40	59.12	2477.44
	$h_2 h_1^{\pm}$	0.00	12.97	4.63	102.39				
	$a_2 h_1^{\pm}$	2.93	0.00	1.71	0.00				
	$th_1^{\pm}$	0.00	0.00	0.00	2.29				
	$tbh_1^{\pm}$	0.00	0.00	0.39	0.00				
Significance		0.11σ	0.35σ	0.13σ	2.39σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		$\gg 3000$	$\gg 3000$	$\gg 3000$	437				
$(>3\ell+>2b_{\mathrm{j}})^{*}$	$h_1^{\pm}h_1^{\mp}$	6.07	3.33	0.12	2.83	0.00	294.55	17.74	33.01
	$h_2 h_1^{\pm}$	0.04	11.13	6.94	11.38				
	$a_2 h_1^{\pm}$	35.14	0.00	4.81	0.00				
	$th_1^{\pm}$	0.00	0.00	25.00	1.32				
	$tbh_1^{\pm}$	0.00	0.00	2.31	0.00				
Significance		2.10σ	0.77σ	2.00σ	0.82σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		567	4216	626	3740				
$(>3\ell+m_{\mathrm{jj}}\sim m_W)^{*}$	$h_1^{\pm}h_1^{\mp}$	6.91	7.73	0.02	45.90	127.55	270.12	63.49	2804.87
	$h_2 h_1^{\pm}$	0.02	16.37	5.87	187.50				
	$a_2 h_1^{\pm}$	17.57	0.00	3.33	0.00				
	$th_1^{\pm}$	0.00	0.00	5.99	6.26				
	$tbh_1^{\pm}$	0.00	0.00	0.00	0.00				
Significance		0.43σ	0.42σ	0.27σ	4.05σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		$\gg 3000$	$\gg 3000$	$\gg 3000$	153				

Table 8. The number of events for a $>3\ell$ final state at $100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC with $14\,\mathrm{TeV}$ center of mass energy. Here $(\ )^{\dagger}$ means $p_T^{\ell_2} \geq 30\,\mathrm{GeV} + p_T^{\ell_3} \geq 40\,\mathrm{GeV}$ whereas $(\ )^{*}$ states that no p_T cuts are added.

Final states		Benchmark Points				Backgrounds			
		BP1	BP2	BP3	BP4	$t\bar{t}$	$t\bar{t}V$	$tZW^{\pm}$	VV/VVV
$3\ell + 1\tau$	$h_1^{\pm}h_1^{\mp}$	95.71	19.59	0.25	83.25	196.24	263.58	75.60	5009.14
	$h_2 h_1^{\pm}$	0.24	38.05	7.08	439.47				
	$a_2 h_1^{\pm}$	468.48	0.00	14.35	0.00				
	$th_1^{\pm}$	0.00	0.00	66.67	7.83				
	$tbh_1^{\pm}$	0.00	0.00	23.14	0.00				
Significance		7.22σ	0.77σ	1.48σ	6.81σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		48	4216	1138	54				

Table 9. The number of events for a $3\ell + 1\tau$ final state at $100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC with $14\,\mathrm{TeV}$ center of mass energy.

of integrated luminosity respectively. However, such tagging does not help for the other BPs, where the presence of both a_1 and $W^{\pm}$s are less in the final sate.

6.3 3τ

In this subsection we consider the case where the τs are coming from the pseudoscalars decay and the decays of gauge bosons, viz., Z boson decays into τ pairs, $W^{\pm}$ boson decays to $\tau\nu$. In this case the multi-tau final state, i.e., $\geq 3\tau$, is almost free from SM backgrounds. Moreover, if we tag such final state with a charged lepton which arises from the $W^{\pm}$ decay, we reduce more efficiently the residual SM backgrounds. The dominant sources for such final state for BP1 and BP4 are $h_1^{\pm} \to a_1 W^{\pm}$ and $h_1^{\pm} \to ZW^{\pm}$ respectively; whereas in the case of BP2 both modes compete, making such final state viable. However, in the case of BP3, such τ state can only appear when the charged Higgs boson is produced in association of a_2 or h_2.

We list the number of the events for $\geq 3\tau$ and $\geq 3\tau + \geq 1\ell$ final states for the benchmark points and the dominant SM backgrounds in table 10. Tagging one charged lepton in the final state makes the gauge boson backgrounds under control. We see that for BP1 the discovery reach can be achieved at $71\,\mathrm{fb}^{-1}$ of integrated luminosity. For the other benchmark points it requires higher luminosities, in particular much more than $3000\,\mathrm{fb}^{-1}$ for BP2. The final state $\geq 3\tau + \geq 1\ell$ will become a possible discovery mode for BP3 and BP4 only in the case of HL-LHC.

6.4 4ℓ

Finally we have considered the multi-leptonic final state with $\geq 4\ell$. The dominant backgrounds are VV and VVV, where V corresponds to Z, $W^{\pm}$ bosons. We report in table 11 the number of events for the signal and the dominant backgrounds. We can see that only BP4 reach a 5σ of discovery within the luminosity of LHC, precisely at $81\,\mathrm{fb}^{-1}$. Such a discovery can be achieved at the HL-LHC in the case of other BPs.

Final states		Benchmark Points				Backgrounds			
		BP1	BP2	BP3	BP4	$t\bar{t}$	$t\bar{t}V$	$tZW^{\pm}$	VV/VVV
$\geq 3\tau$	$h_1^{\pm}h_1^{\mp}$	26.69	1.62	0.20	4.22	0.00	23.42	4.94	964,12
	$h_2 h_1^{\pm}$	0.11	5.38	1.78	19.85				
	$a_2 h_1^{\pm}$	204.96	0.00	8.52	0.00				
	$t h_1^{\pm}$	0.00	0.00	10.00	0.47				
	$t b h_1^{\pm}$	0.00	0.00	1.93	0.00				
$+ \geq 1\ell$	$h_1^{\pm}h_1^{\mp}$	7.20	0.48	0.04	1.00	0.00	5.19	0.77	68.67
	$h_2 h_1^{\pm}$	0.03	1.55	0.30	6.36				
	$a_2 h_1^{\pm}$	64.42	0.00	1.94	0.00				
	$t h_1^{\pm}$	0.00	0.00	5.00	0.00				
	$t b h_1^{\pm}$	0.00	0.00	0.77	0.00				
Significance		5.92σ	0.19σ	0.88σ	0.81σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		71	$\gg 3000$	3190	3784				

Table 10. The number of events for a $> 3\tau$ final state at $100\,\mathrm{fb}^{-1}$ of luminosity at the LHC with $14\,\mathrm{TeV}$ center of mass energy.

Final states		Benchmark Points				Backgrounds			
		BP1	BP2	BP3	BP4	$t\bar{t}$	$t\bar{t}V$	$tZW^{\pm}$	VV/VVV
$\geq 4\ell$ $+p_T^{\ell_1} \geq 50\,\mathrm{GeV}$ $+p_T^{\ell_2} \geq 40\,\mathrm{GeV}$	$h_1^{\pm}h_1^{\mp}$	14.80	11.27	0.12	44.96	0.00	215.85	59.13	2423.16
	$h_2 h_1^{\pm}$	0.02	27.12	2.59	255.43				
	$a_2 h_1^{\pm}$	29.28	0.00	3.24	0.00				
	$t h_1^{\pm}$	0.00	0.00	16.67	3.50				
	$t b h_1^{\pm}$	0.00	0.00	3.86	0.00				
Significance		0.84σ	0.73σ	0.51σ	5.55σ				
$\mathcal{L}_{5\sigma}$ (fb^{-1})		3543	4691	$\gg 3000$	81				

Table 11. The number of events for a 4ℓ final state at $100\,\mathrm{fb}^{-1}$ of luminosity at the LHC with $14\,\mathrm{TeV}$ center of mass energy. The p_T of the first lepton is greater than $50\,\mathrm{GeV}$ whereas the p_T of the second lepton is greater than $40\,\mathrm{GeV}$. No selections are applied on the other leptons.

7 Reconstruction of the charged Higgs boson

In this section we concentrate on the final states appropriate to the respective decay channels which can be used to reconstruct the charged Higgs boson mass, i.e., $m_{h_1^{\pm}}$. We can see from table 5 that for BP1, $h_1^{\pm} \to a_1 W^{\pm}$ and for BP4, $h^{\pm} \to ZW^{\pm}$ are the most dominant decay modes, that manifest the existence of light pseudoscalar and the triplet nature of the charged Higgs boson respectively. The light pseudoscalar mass can be reconstructed via the invariant mass of b-jet and τ-jet pairs as can be seen from figure 4(c) and figure 4(d)
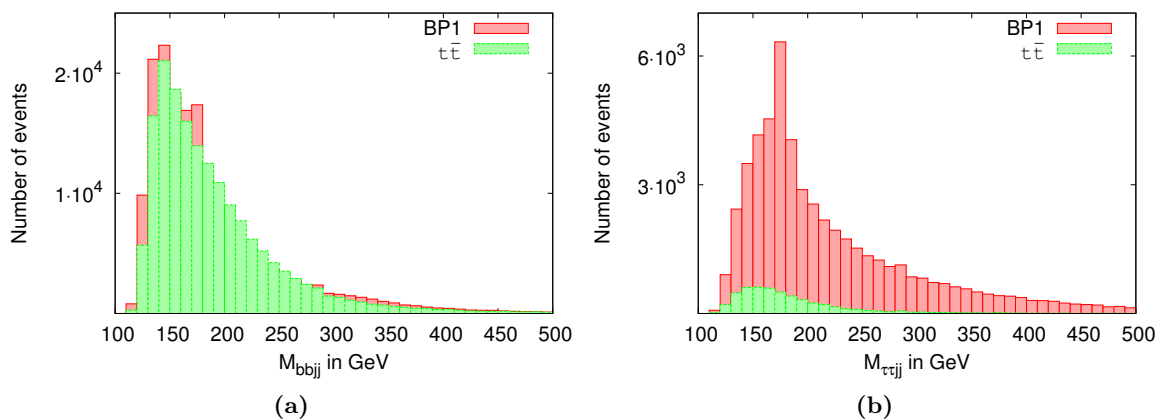
Figure 5. Invariant mass distributions for the reconstruction of the charged Higgs boson mass for the benchmark points. (a) describes $bbjj$ invariant mass distributions, where b-jet pairs are coming from a_1 peak and normal jet pairs are coming from $W^\pm$ peak. (b) shows $\tau\tau jj$ invariant mass distribution where τ-jet pairs are coming from a_1 mass peak and the normal jet-pairs are coming from $W^\pm$ mass peak respectively.

respectively. For this purpose we first reconstruct a_1 mass peak via $b\bar{b}$ decay mode and we consider b-jets within $\pm 7.5\,\mathrm{GeV}$ of the b-jet invariant mass distribution around the a_1 mass peak for the reconstruction of the charged Higgs boson. Similarly we reconstruct $W^\pm$ mass peak from di-jet invariant mass distribution. Next the b-jets from the selected window around the a_1 peak are taken along with the jets within the $W^\pm$ mass window for the $2b2j$ invariant mass reconstruction. Figure 5 (a) shows such distributions for the BP1 together with the dominant SM background $t\bar{t}$. It is clearly visible that for BP1, invariant mass distribution has a local peak around $180\,\mathrm{GeV}$, which manifests the charged Higgs boson mass peak.

Next we move to $2\tau 2j$ invariant mass distribution, showed in figure 5(b), where the τ-jets are coming from the $\pm 10\,\mathrm{GeV}$ window of the a_1 mass peak and the normal jet pair is taken from $\pm 10\,\mathrm{GeV}$ of the $W^\pm$ mass window. Clearly we see from figure 5 that $2\tau 2j$ peak is much more clear than $2b2j$ but reconstruction of both require very high luminosity run at the LHC. Because $\mathcal{B}(a_1 \to \tau\bar{\tau}) \sim 10\%$, a better negotiation would be to tag one pair of b coming from the decay of one pseudosclar and one pair of τ from the other one, where both the pseudoscalars come from the decays of the charged Higgs pair. Here we reconstruct such light pseudoscalar mass peak from the invariant mass distributions of b-jet and τ-jet pair.

In table 12 we present the final state numbers for the benchmark points and the dominant SM backgrounds to probe $h^\pm \to a_1 W^\pm$ decay modes. The significance (required luminosity for 5σ discovery) for the benchmark points are given in the last column. The final state is comprised of $\geq 2\tau - \mathrm{jets} + \geq 2b - \mathrm{jets} + \geq 1\ell$, where the τs and bs are coming from the light pseudoscalar and one charged lepton can from one of the two $W^\pm$ bosons coming from charged Higgs pair. After that selection events within $\pm 10\,\mathrm{GeV}$ of a_1 mass peak via b-jet pair invariant mass have been chosen and presented in table 12

	Signals					Backgrounds				Significance
	$h_1^\pm h_1^\mp$	$h_2 h_1^\pm$	$a_2 h_1^\pm$	$t h_1^\pm$	$tb h_1^\pm$	$t\bar{t}$	$t\bar{t}V$	$tZW^\pm$	VV/VVV	$\mathcal{L}_{5\sigma}$ (fb^{-1})
BP1	6.81	0.04	23.42	0.00	0.00	0.00	1.41	0.01	0.10	5.37σ (87)
BP2	0.07	0.34	0.00	0.00	0.00	0.00	1.57	0.01	0.10	0.28σ ($\gg$ 3000)
BP3	0.01	0.19	0.56	0.00	0.39	0.00	1.20	0.01	0.00	0.75σ (4471)
BP4	0.17	0.45	0.00	0.02	0.00	0.00	2.15	0.01	0.00	0.40σ ($\gg$ 3000)

Table 12. The number of event combination of b-jet pair at $100\,\text{fb}^{-1}$ integrated luminosity, where b-jets are within $\pm 10\,\text{GeV}$ of a_1 mass peak in a final state comprised of $\geq 2\tau-\text{jets}+ \geq 2\text{b}-\text{jets}+ \geq 1\ell$. The significance (required luminosity for 5σ discovery) for the benchmark points are given in the last column.

	Signals					Backgrounds				Significance
	$h_1^\pm h_1^\mp$	$h_2 h_1^\pm$	$a_2 h_1^\pm$	$t h_1^\pm$	$tb h_1^\pm$	$t\bar{t}$	$t\bar{t}V$	$tZW^\pm$	VV/VVV	$\mathcal{L}_{5\sigma}$ (fb^{-1})
BP1	7.79	0.06	38.06	0.00	0.00	0.00	0.58	0.00	0.00	6.73σ (55)
BP2	0.10	1.03	0.00	0.00	0.00	0.00	0.37	0.00	0.00	0.92σ (2937)
BP3	0.18	0.79	3.43	4.50	0.00	0.00	0.58	0.00	0.00	2.89σ (299)
BP4	0.00	0.45	0.00	0.01	0.00	0.00	0.74	0.01	0.00	0.42σ ($\gg$ 3000)

Table 13. The number of event combination of τ-jet pair at $100\,\text{fb}^{-1}$ integrated luminosity, where τ-jets are within $\pm 10\,\text{GeV}$ of a_1 mass peak in a final state comprised of $\geq 2\tau-\text{jets}+ \geq 2\text{b}-\text{jets}+ \geq 1\ell$. The significance (required luminosity for 5σ discovery) for the benchmark points are given in the last column.

at an integrated luminosity $100\,\text{fb}^{-1}$. It can be seen that only for BP1, whose dominant decay mode is $h^\pm \to a_1 W^\pm$, a discovery of 5.37σ can be achieved at $100\,\text{fb}^{-1}$ of integrated luminosity. For other benchmark points one needs very high luminosities, as can be read from table 12.

Similarly table 13 presents the final states comprised of $\geq 2\tau-\text{jets}+ \geq 2\text{b}-\text{jets}+ \geq 1\ell$, where the τs and bs are coming from the light pseudoscalar and one charged lepton come from one of the two $W^\pm$ bosons coming from charged Higgs pair. However, in this case we select the events for which the τ-jet pairs falls within $\pm 10\,\text{GeV}$ of a_1 mass peak. The significance at an integrated luminosity of $100\,\text{fb}^{-1}$ (required luminosity for 5σ discovery) for the benchmark points are given in the last column of table 13. In this case also BP1 reaches a signal significance of 6.73σ whereas for the other benchmark points a discovery of 5σ requires higher luminosities.

We now move to reconstruct the charged Higgs mass via its triplet nature, i.e. via $h_1^\pm \to ZW^\pm \to 2l2j$. The presence of multiple charged leptons makes the final state much cleaner and can be probed with relatively earlier data. Figure 6 shows the invariant mass distribution of di-lepton and di-jet, i.e. $m_{\ell\ell jj}$, where the di-leptons are coming from the Z boson and are selected within $\pm 5\,\text{GeV}$ of Z mass peak of the di-lepton invariant mass distribution ($m_{\ell\ell}$) and di-jets are coming from the W boson, which are selected when they fall within $\pm 10\,\text{GeV}$ of the di-jet invariant mass distribution m_{jj}. We can see that for BP4
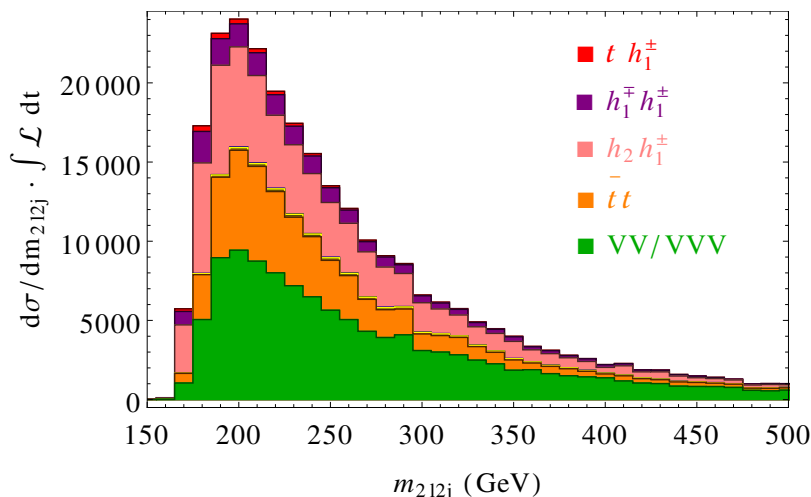
Figure 6. Invariant mass distribution $m_{2\ell 2j}$ for BP4 and the dominant SM backgrounds at $100\,\mathrm{fb}^{-1}$ of integrated luminosity. The number of events for the signals $h_1^{\pm}h_1^{\mp}$, $h_2 h_1^{\pm}$ and $th_1^{\pm}$ are multiplied by a factor of 50 for the sake of the presentation.

	Signals					Backgrounds				Significance
	$h_1^{\pm}h_1^{\mp}$	$h_2 h_1^{\pm}$	$a_2 h_1^{\pm}$	$th_1^{\pm}$	$tbh_1^{\pm}$	$t\bar{t}$	$t\bar{t}V$	$tZW^{\pm}$	VV/VVV	$\mathcal{L}_{5\sigma}$ (fb^{-1})
BP1	1.09	0.00	8.78	0.00	0.00	29.44	20.69	4.36	450.65	0.43σ ($\gg 3000$)
BP2	0.77	2.03	0.00	0.00	0.00	9.81	15.52	3.49	87.24	0.26σ ($\gg 3000$)
BP3	0.00	0.57	0.14	1.50	0.00	9.81	18.00	4.56	148.70	0.16σ ($\gg 3000$)
BP4	5.83	31.12	0.00	1.27	0.00	19.62	15.26	3.39	339.84	1.87σ (712)

Table 14. The number of event combination for $m_{\ell\ell jj}$ at $100\,\mathrm{fb}^{-1}$ integrated luminosity, where ℓ are within $\pm 5\,\mathrm{GeV}$ of Z mass peak and normal jets are within $\pm 10\,\mathrm{GeV}$ of $W^{\pm}$ mass peak.

it is possible to achieve the reconstructed charged Higgs mass peak via $h_1^{\pm} \to ZW^{\pm}$ mode. Table 14 shows the reconstructed event combinations within $\pm 10\,\mathrm{GeV}$ of the charged Higgs mass peak for the benchmark points and the corresponding total SM background numbers. It is clearly seen that only for BP4 a discovery of 5σ can be achieved below $1000\,\mathrm{fb}^{-1}$ (712) of integrated luminosity. For the rest of the points one needs very high luminosity run of LHC ($\gg 3000\,\mathrm{fb}^{-1}$). Thus a perfectly triplet-like singly charged Higgs boson can be easily probed via $ZW^{\pm}$ decay modes, which is not possible for a doublet-like or a mixed charged Higgs boson at the LHC run-I.

8 Distinguishing from other extended scenario

In the previous sections we have discussed the theoretical and phenomenological aspects of a charged Higgs boson in the context of the TNMSSM. This model is characterized by the presence of a light pseudoscalar in the spectrum, which allows the decay channel $h_1^{\pm} \to a_1 W^{\pm}$, as well as by the triplet-like decay channel $h_1^{\pm} \to ZW^{\pm}$. The light pseudoscalar, together with the $h^{\pm} \to aW^{\pm}$ decay mode, is also present in NMSSM [11] and its
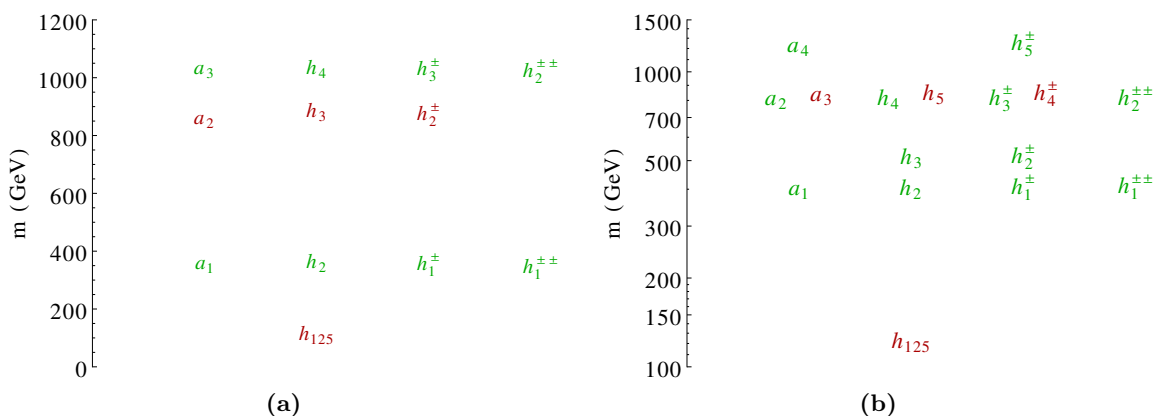
Figure 7. A typical mass hierarchy of the scalar sector, with the doublets in red and the triplet Higgs bosons in green color. We have considered an extension of the MSSM with a $Y = \pm 1$ triplet (a) and the custodial limit of an extension of the MSSM with both $Y = 0$ and $Y = \pm 1$ triplets (b).

phenomenology has been well studied for a doublet-like charged Higgs boson [56–58]. Similarly the presence of $ZW^\pm$ decay demonstrates a triplet-like charged Higgs boson which breaks custodial symmetry [5, 10]. However, TNMSSM gives an opportunity to have both the decay modes. This enables us to straightway separate the models from completely doublet-type charged Higgs boson(s) and completely triplet-type charged Higgs bosons.

We have considered various benchmark points in order to probe these two different decay modes of the lightest charged Higgs boson and it has been found that both $h^\pm \to aW^\pm$ and $h_1^\pm \to ZW^\pm$ are unlikely to happen for a parameter point. Confronting table 2 and table 6 we see that, apart from the pair production cross section, the relevant production channel for a triplet charged Higgs boson is either in association with a_2 or h_2. The associated production cross-sections for both BP1 and BP4 are the same, $\sim 300\,\mathrm{fb}$, because of the apparent mass degeneracy among $h_1^\pm$ and a_2/h_2 respectively.

The tendency of the gauge representation to group in the same mass value for scalar, pseudoscalar and charged Higgs bosons was pointed out recently [23]. Here we want to emphasize that this is true even in the case of other possible triplet extensions of the MSSM. In figure 7 we present the scalar mass spectrum for two different triplet extensions of the MSSM. In figure 7 (a) we have considered the extension of the MSSM with a $Y = \pm 1$ triplet superfield [8], whereas in figure 7 (b) the case where both the $Y = 0$ and $Y = \pm 1$ triplet superfields (custodial triplets) are present [10]. The phenomenology of the $Y = \pm 1$ triplet was studied in [59] whereas the model with triplets in the custodial symmetric limit was analyzed in [60, 61]. We have selected the two sample points scanning over the parameter space and requesting the presence the doublet-type lightest scalar Higgs boson $h_1 \equiv h_{125}$ with a tree-level mass $\sim 125\,\mathrm{GeV}$. In both the case there are two doubly-charged charged Higgs bosons in the spectrum, because of the presence of the $Y = \pm 1$ triplets. We can see that these doubly-charged states are degenerate in mass with one of the triplet neutral scalars, pseudoscalars and one of the triplet-like singly-charged Higgs bosons. Such scenarios thus claim to have one doubly charged Higgs boson in the similar mass range

of the triplet-like singly charged Higgs boson and finding both will surely shed light on the existence of the multiple $SU(2)_L$ triplets in the spectrum including the one with non-zero hypercharge. The doubly charged Higgs boson phenomenologies are independently studied in [8, 10, 59–61]. Thus finding a triplet-like singly charged Higgs boson and one neutral scalar (a_2/h_2) with the same mass but no doubly charged Higgs bosons is a proof of existence of a $Y = 0$ triplet in the spectrum. However, the existence of mass degenerate triplet-like doubly charged Higgs boson with or without additional neutral scalars along with the triplet-like singly charged Higgs boson in the mass spectrum surely tells about the existence of multiple $SU(2)_L$ triplets, i.e. $Y = \pm 1$ and $Y = 0, \pm 1$ respectively. The search modes discussed in this article separate doublet- and triplet-like singly charged Higgs bosons with standard or non-standard decay modes. On top of the mass degeneracy information, existence/non-existence of a doubly charged Higgs boson will give us addition handle to pin down about the others gauge representation in the Higgs potential that plays a crucial role in electro-weak symmetry breaking.

The Higgs phenomenology of the extended Higgs sector in non-supersymmetric models is very similar to the supersymmetric case. The existence of the light pseudoscalar, i.e. the pseudo-Nambu-Goldstone boson, of course will be governed by the breaking of the global U(1) symmetry of the scalar potential. Similar to the supersymmetric case this corresponds to small Higgs trilinear couplings $A_i H_i^\dagger T H_i$ [65], which breaks this global symmetry. There are very limited analysis for triplet-like light pseudoscalar as pNGB mode for non-supersymmetric theories, however there are plenty of studies on the Higgs phenomenology with different hypercharged triplet [66–70].

9   Conclusions

In this article we prescribe some search modes for light singly charged Higgs boson via which we can shed light on the gauge representation of the charged Higgs bosons. A triplet-like charged Higgs boson does not couple to fermions, thus neither it is possible to produce it via fermionic modes nor it decays in the fermionic modes, i.e. $\tau\nu$ and/or tb. However a triplet-charged Higgs boson couples to $ZW^\pm$, which gives rise to additional production and decay modes. We explore these features in order to separate a triplet-like singly charged Higgs boson from a doublet one, even in the presence of a light-pseudoscalar, which gives rise to an additional decay mode, i.e. $a_1 W^\pm$.

We have analyzed signatures of a supersymmetric extension of the SM, characterized by an extra $Y = 0$ Higgs triplet and a SM gauge singlet, in view of the recent and previous Higgs data. We have chosen different benchmark points which represent different decay modes preferred either by a triplet-like or by a doublet-like charged Higgs boson. In particular, BP3 represents a completely doublet-like charged Higgs boson and BP4 represents a completely triple-like charged Higgs bosons. In the case of BP1, $a_1 W^\pm$ mode is the most dominant, whereas in BP2 we have mixed scenario. We have seen that a BP1 like scenario with dominant decay mode in $a_1 W^\pm$ can be probed at the LHC with $14\,\mathrm{TeV}$ of ECM with very early data of $\sim 43\,\mathrm{fb}^{-1}$ integrated luminosity via $2b + 2\tau + 1\ell + m_{jj} \sim m_W$ final state.

The discovery of such light pseudoscalar can be achieved with very early data of $\sim 55\,\mathrm{fb}^{-1}$ and this would be certainly a signal in favor of an extended Higgs sectors. The NMSSM does have such light pseudoscalar but does not have any extra charged Higgs bosons compared to the MSSM, while the TNMSSM has an extra triplet-like charged Higgs boson. This possibility, changes the direct bounds derived from searches for a charged Higgs at the LHC, as well as the indirect bounds on flavour. These changes are due to the doublet-triplet mixing in the charged Higgs and chargino sectors of the triplet extended model [62–64].

The triplet-like charged Higgs boson and its decay mode to $ZW^{\pm}$ can be probed via $3\ell + 1\tau$ with an early data of $\sim 54\,\mathrm{fb}^{-1}$ of integrated luminosity. The charged Higgs mass can be reconstructed with relatively larger data of $\sim 712\,\mathrm{fb}^{-1}$. Finding such triplet-charged state would clearly be proof of the existence of higher representation of $\mathrm{SU}(2)_L$ in the Higgs potential. We have also presented the sensitivity in other possible search modes.

The existence of non-zero hypercharge triplets would require to have more than one doubly charged Higgs boson degenerate along with the singlet triplet-like charged Higgs bosons. Finding such doubly charged states are necessary in order to prove the existence of the triplet representation with non-zero hypercharge.

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