Same-sign Charged Higgs Pair Production in bosonic decay channels at the HL-LHC and HE-LHC

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Abstract

Same-sign charged Higgs pair production via vector-boson scattering is a useful probe of the mass spectrum among the heavier scalar, pseudoscalar, and charged Higgs bosons in two-Higgs-doublet models. It has been shown that the production cross section scales as the square of the mass difference $\Delta m = (m_{H^0} - m_{A^0})$ in the alignment limit ($\cos(\beta - \alpha) = 0$). We study the potential measurement of this same-sign charged Higgs pair production at the high-luminosity LHC (HL-LHC) and the proposed 27 TeV $pp$ collider, with emphasis in the decay channel $H^\pm H^\pm \to (W^\pm A^0)(W^\pm A^0)$, which is in general the dominant mode when the charged Higgs mass is above the $W^\pm A^0$ threshold. We also examine the current allowed parameter space taking into account the theoretical constraints on the model, the electroweak precision measurements, $B$ decays, and direct searches in the $H^\pm \to \tau^\pm \nu_\tau$ and $H^\pm \to W^\pm A^0 \to (\ell^\pm \nu_\ell)(\mu \mu)$. 
I. INTRODUCTION

Since the discovery of a Higgs-like particle at the CERN Large Hadron Collider (LHC) in 2012, there have been many theoretical and phenomenological studies dedicated to non-minimal Higgs sector models that can explain the observed Higgs-like particle and account for some weakness of the Standard Model (SM). One common feature of many extensions of the minimal Higgs sector is the presence of extra neutral Higgs bosons as well as singly-charged Higgs bosons in the physical spectrum. Therefore, the discovery of charged Higgs bosons would be an unambiguous sign of physics beyond the SM. One of the most popular models with extended Higgs sector is the two-Higgs-Doublet Model (2HDM) \[1\] in which one introduces two Higgs doublet fields to break the $SU_L(2) \times U_Y(1)$ symmetry down to the $U(1)_{em}$ symmetry. In order to avoid tree-level flavor-changing neutral current couplings, one can advocate a natural flavor conservation imposed by a discrete $Z_2$ symmetry \[2\]. Depending on the Higgs and fermion field transformations under the $Z_2$, one can have a number of Yukawa textures for the fermion sector, denoted by Type I to IV 2HDM’s. After electroweak symmetry breaking driven by the two Higgs fields takes place, the physical spectrum of the model consists of 2 CP-even Higgs bosons $h^0, H^0$ (one of them could be identified as the observed 125 GeV Higgs-like particle), a CP-odd Higgs boson $A^0$ and a pair of charged Higgs bosons $H^\pm$.

At hadron colliders, charged Higgs bosons can be produced in a number of channels. An important source of light charged Higgs bosons is from $t \bar{t}$ production, followed by the top decay into a charged Higgs boson and a bottom quark if kinematically allowed. Other important mechanisms for singly-charged Higgs production are the QCD processes $gb \rightarrow tH^-$ and $gg \rightarrow tbH^-$ \[3\]. We refer to Ref. \[4\] for an extensive review on charged Higgs phenomenology. Charged Higgs bosons have been searched for in the past at both LEP \[5\] and Tevatron \[6\]. An upper limit of the order of 80 GeV has been set at LEP experiments both from fermionic and bosonic decays $H^\pm \rightarrow W^\pm A^0$ \[5\]. While at the Tevatron a search for the charged Higgs from top decay had been performed in various decay channels of $H^\pm$ and limits on $B(t \rightarrow H^+b)$ have been set \[6\]. At the LHC, one can search for light $H^\pm$ from top decay and for heavy $H^\pm$ from $gb \rightarrow tH^-$ and $gg \rightarrow tbH^-$. Light charged Higgs boson ($\leq m_t - m_b$) would decay dominantly into $\tau \nu_\tau, c \bar{s}$ or $c \bar{b}$ final states. In case of light pseudoscalar boson $A^0$, $H^\pm$ can also decay into $W^\pm A^0$. However, a heavy $H^+$ can also decay
into $t\bar{b}$, $W+h$, $W+A^0$, or $W+H^0$ if kinematically open. Both at the LHC Run-1 and Run-2, ATLAS and CMS had already set exclusion limits on $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau^+\nu_\tau)$ [7–12], which can be used to set limits on $\tan\beta$ for a given charged Higgs mass less than $\lesssim m_t - m_b$. Moreover, from $t \rightarrow bH^+$ there has been also a search for $H^+ \rightarrow c\bar{s}$ channel both by ATLAS and CMS [13] at 7 TeV and 8 TeV. The limit obtained on $B(t \rightarrow bH^+)$ is rather weak compared to $\tau\nu_\tau$ mode. Both ATLAS and CMS also searched for $H^\pm \rightarrow tb$ decay, in which no $H^\pm$ signal was observed and upper limits on the $\sigma(pp \rightarrow tbH^\pm) \times B(H^\pm \rightarrow tb)$ are set [14–17].

In the 2HDM, it has been shown [18–20] that the charged Higgs boson can decay dominantly into the bosonic final state $H^\pm \rightarrow W^\pm A^0$ when kinematically open. Other models beyond SM could also have similar features such as 2HDM with singlet scalars [21] and also the next-to-minimal supersymmetric standard model [22]. At LEPII [23], pair-produced charged Higgs bosons have been searched in various final states, including $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$, $c\bar{s}\bar{c}s$, $c\bar{s}\tau^-\bar{\nu}_\tau$, $W^*AW^*A$ and $W^*A\tau^-\bar{\nu}_\tau$, and an upper limit of the order 80 GeV was set on the charged Higgs mass. Recently, CMS also performed a search for such bosonic decays of the charged Higgs [24]. The study was only dedicated to light charged Higgs produced from top decay followed by $H^\pm \rightarrow W^\pm A^0$, where $A^0$ decays into a pair of muons and $W^\pm$ decays into a charged lepton ($e, \mu$) and a neutrino. Assuming that $H^\pm$ decays 100% into $W^\pm A^0$ and $B(A^0 \rightarrow \mu\mu) = 3 \times 10^{-4}$, CMS set a new and first limit from bosonic decay of $H^\pm$ on $B(t \rightarrow bH^+)$. Recently, Ref. [25] proposed a new mechanism where a pair of same-sign charged Higgs bosons are produced via vector boson fusion (VBF) at hadron colliders. Such a process can shed some light on the global symmetry of the underlying scalar potential. Assuming that the charged Higgs bosons decay into $\tau\nu_\tau$ or $tb$, Ref.[25] evaluated the signal and the SM backgrounds, and discussed the feasibility of the new process both for the high-luminosity LHC (HL-LHC) with 14 TeV center of mass energy and also for the future high-energy LHC (HE-LHC) 27 TeV.

In this work, motivated by the recent CMS search for the bosonic decay $H^\pm \rightarrow W^\pm A^0$, we investigate same-sign charged Higgs production from VBF, followed by bosonic decays of the charged Higgs boson:

$$pp \rightarrow W^\pm W^{*}\rightarrow jjH^\pm H^\pm \rightarrow jj(W^\pm A^0)(W^\pm A^0).$$
in Type-I and III 2HDM’s. We calculate the signal and various SM backgrounds, and estimate the sensitivity at the HL-LHC as well as for the future hadron collider HE-LHC with 27 TeV center of mass energy.

We should emphasize, instead of studying each new scalar (or two of them) in different processes separately, the novel process we consider here involves the effects of all new scalar masses. It means that we have the chance to simultaneously test the whole mass spectrum in the 2HDM for some specific mass relations via a single process. Finally, we show that the mass spectrum of $m_{A^0} = 30 - 100$ GeV and $\Delta m \equiv m_{H^0} - m_{A^0} = 200 - 250$ GeV in Type-I and III 2HDM’s can be explored at the HE-LHC in the near future.

The organization is as follows. In the next section, we describe briefly the 2HDM’s and relevant interactions. In Sec. III, we discuss the constraints on the model from theoretical requirements, electroweak precision measurements, $B$ decays, and direct searches. In Sec. IV, we calculate the same-sign charged Higgs production cross sections, and perform the signal-background analysis. We conclude in Sec. V.

II. BRIEF REVIEW OF TWO-HIGGS-DOUBLET MODELS

In the two-Higgs-Doublet Model (2HDM), two Higgs doublet fields $\Phi_{1,2}$ with hypercharge $Y_{\Phi_{1,2}} = 1/2$ are introduced. The most general renormalizable scalar potential, which respects the $SU_L(2) \otimes U_Y(1)$ gauge symmetry, has the following form:

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 \left( \Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} \left( \Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left( \Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[ \left( \Phi_1^\dagger \Phi_2 \right)^2 + \left( \Phi_2^\dagger \Phi_1 \right)^2 \right]$$

(2)

where $m_{11}^2$, $m_{22}^2$ and $\lambda_{1,2,3,4}$ are real, while $m_{12}^2$ and $\lambda_5$ could be complex for CP violation purpose.

Assuming that both $\Phi_1$ and $\Phi_2$ acquire a vacuum expectation value (VEV) $v_{1,2}$ that can induce electroweak symmetry breaking, the two complex scalar $SU_L(2)$ doublets can be decomposed according to

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \rho_i + i \eta_i) / \sqrt{2} \end{pmatrix}, \quad i = 1, 2.$$
The mass eigenstates for the Higgs sector are obtained by orthogonal transformations,
\[
\begin{pmatrix}
\phi_1^+ \\
\phi_2^+
\end{pmatrix} = R_\beta \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}, \quad \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = R_\alpha \begin{pmatrix} H^0 \\ h^0 \end{pmatrix}, \quad \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = R_\beta \begin{pmatrix} G^0 \\ A^0 \end{pmatrix},
\]
with the generic form \((\theta = \alpha, \beta)\)
\[
R_\theta = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}.
\]

From the eight degrees of freedom initially present in the two scalar doublets, three of
them, namely the Goldstone bosons \(G^\pm\) and \(G^0\), are eaten by the longitudinal component of
\(W^\pm\) and \(Z^0\), respectively. The remaining five degrees of freedom should manifest as physical
Higgs bosons: two CP-even \(H^0\) and \(h^0\), one CP-odd \(A^0\), and a pair of charged scalars \(H^\pm\). In
the CP conserving case, the above potential contains 10 parameters (including the VEV’s
of the Higgs doublets). \(m_{12}^2\) and \(m_{22}^2\) can be eliminated by the use of the 2 minimization
conditions. One of the VEV’s can be traded from the \(W\) mass as a function of the ratio \(\tan \beta \equiv v_2/v_1\). We are then left with seven independent parameters which can be taken as:
the four physical masses \(m_h, m_H, m_A\) and \(m_{H\pm}\), CP-even mixing angle \(\alpha\), \(\tan \beta\),
and \(m_{12}^2\).

In order to avoid Flavor-Changing Neutral Current (FCNC), a discrete symmetry \(Z_2\)
(where for example \(\Phi_1 \to \Phi_1\) and \(\Phi_2 \to -\Phi_2\)) is imposed [2]. Note that in the above
potential, \(Z_2\) symmetry is only violated by the dimension-two term \(m_{12}^2\). Depending on the
\(Z_2\) charge assignment to the lepton and quark fields [1, 26], one can have 4 different types
of Yukawa textures. In type-I model, only the second doublet \(\Phi_2\) interacts with all the
fermions like in the SM while in the type-II model \(\Phi_1\) interacts with the charged leptons and
down-type quarks and \(\Phi_2\) interacts with up-type quarks. In type-III model, charged leptons
couple to \(\Phi_1\) while all the quarks couple to \(\Phi_2\). Finally, in type-IV model down-type quarks
acquire masses from their couplings to \(\Phi_1\) while charged leptons and up-type quarks couple
to \(\Phi_2\). The most general Yukawa interaction can be written as follows [1],
\[
-L_{2\text{HDM}}^\text{Yukawa} = \overline{Q}_L Y_u \Phi_2 u_R + \overline{Q}_L Y_d \Phi_d d_R + \overline{L}_L Y_\ell \Phi_\ell \ell_R + \text{h.c},
\]
where \(\Phi_{d,l} (d, l = 1, 2)\) represent \(\Phi_1\) or \(\Phi_2\), \(Y_f (f = u, d \text{ or } \ell)\) stand for \(3 \times 3\) Yukawa matrices
and \(\Phi_2 = i\sigma_2 \Phi_2^*\).

Writing the Yukawa interactions eq. \((5)\) in terms of mass eigenstates of the neutral and
TABLE I. Yukawa coupling coefficients $\xi^{A_0}$ to the up-quarks, down-quarks and the charged leptons $(u,d,\ell)$ in the four 2HDM types.

| type | $\xi_u^{A_0}$ | $\xi_d^{A_0}$ | $\xi_\ell^{A_0}$ |
|------|---------------|---------------|------------------|
| I    | $\cot \beta$ | $-\cot \beta$ | $-\cot \beta$   |
| II   | $\cot \beta$ | $\tan \beta$  | $\tan \beta$    |
| III  | $\cot \beta$ | $-\cot \beta$ | $\tan \beta$    |
| IV   | $\cot \beta$ | $\tan \beta$  | $-\cot \beta$   |

charged Higgs bosons yields

$$-\mathcal{L}_{Yukawa}^{2HDM} = \sum_{f=u,d,\ell} m_f \left( \xi_f^{h^0} \bar{f} f h^0 + \xi_f^{H^0} \bar{f} f H^0 - i \xi_f^{A_0} \bar{f} \gamma_5 f A^0 \right)$$

$$+ \left\{ \sqrt{2} V_{ud} \frac{\bar{u}}{v} \left( m_u \xi_u^{A_0} P_L + m_d \xi_d^{A_0} P_R \right) dH^+ + \frac{\sqrt{2} m_\ell \xi_\ell^{A_0}}{v} \bar{\ell} \gamma_5 \ell H^+ + \text{h.c} \right\},$$

where $v^2 = v_1^2 + v_2^2 = (2\sqrt{2}G_F)^{-1}$; $P_R$ and $P_L$ are the right- and left-handed projection operators, respectively. The coefficients for $\xi_f^{A_0}$ ($f = u, d, l$) in the four 2HDM types, which are relevant to this work, are given in the Table I.

III. CONSTRAINTS

We consider both the theoretical and experimental constraints on 2HDM’s.

A. Theoretical and electroweak precision constraints

For theoretical constraints we take into account all set of tree-level perturbative unitarity conditions [27]. We also require that all $\lambda_i$’s remain perturbative. Moreover, we demand that the potential remains bounded from below when the Higgs fields become large in any direction of the field space [1], which requires the following set of constraints:

$$\lambda_1 > 0 \, , \, \lambda_2 > 2 \, , \, \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \min(0, \lambda_4 + \lambda_5, \lambda_4 - \lambda_5).$$

For experimental constraints we can further divide them into indirect and direct searches. The indirect searches mainly arise from Electro-Weak Precision Observable (EWPOs) and flavor physics. The EWPOs can be represented by a set of oblique parameters $S, T$ and
FIG. 1. The allowed parameter space in the plane of \((\Delta m \equiv m_{H^0} - m_{A^0}, m_{H^\pm})\) due to the constraints from the oblique \(S\) and \(T\) parameters, and all theoretical constraints. The upper panels are for \(m_{A^0} = 65\) GeV while the lowers for \(m_{A^0} = 100\) GeV, in which \(\tan\beta = 2.6\) (left), 5 (middle), and 10 (right) are shown. The green points are right at the alignment limit \(\sin(\beta - \alpha) = 1\) while the red points satisfy \(0.97 < \sin(\beta - \alpha) < 1\) (near alignment limit).

\(U\). From 2018 Particles Data Group (PDG) review [28] with a fixed \(U = 0\), the best fit of \(S, T\) parameters can be represented as \(S = 0.02 \pm 0.07\) and \(T = 0.06 \pm 0.06\). We emphasize that the \(T\) parameter, which is related to the amount of isospin violation, is sensitive to the mass splitting among \(H^\pm, H^0\), and \(A^0\). It will restrict the allowed mass spectrum for the scalars in our analysis below. In order to fulfill the \(T\) constraint in the 2HDM, the spectrum should be chosen close to the approximate custodial symmetry [29], which is satisfied in one of the following limits: i) \(m_{H^\pm} = m_{A^0}\), ii) \(m_{H^\pm} = m_{H^0}\) together with \(\sin(\beta - \alpha) = 1\), or iii) \(m_{H^\pm} = m_{H^0}\) together with \(\cos(\beta - \alpha) = 1\).
As mentioned before, the oblique parameter $T$ is highly sensitive to the mass splitting among $H^\pm$, $H^0$, and $A^0$. In order to obtain the allowed parameter space for the mass of charged Higgs boson and the mass splitting $\Delta m = m_{H^0} - m_{A^0}$, we consider all the above theoretical constraints and $3\sigma$ allowed regions of the $S$ and $T$ parameters in Fig. 1 for $\tan \beta = 2.6$, 5, and 10 with $m_{A^0} = 65$ and 100 GeV, respectively. We also scan on $m_{12}^2$ in the following range $[0, 10^6]$ GeV$^2$ in order to satisfy the perturbative unitarity and vacuum stability constraints for a fixed set of physical masses and mixings. We notice that, in our parameter space, the $S$ parameter is always within the best-fit range while the $T$ parameter severely constrains the splitting between $m_{A^0}$ and $m_{H^\pm}$, and also $\Delta m$.

For $\tan \beta = 2.6$, there is no significant difference in the allowed region between the alignment limit $\sin(\beta - \alpha) = 1$ and the near-alignment limit $0.97 < \sin(\beta - \alpha) < 1$. In the case where $\tan \beta = 5$, one can see that $\Delta m$ is constrained to be less than about 200 GeV in the exact alignment limit. This cut on $\Delta m$ is in fact due to the vacuum stability constraints in Eq.(7), where either $\lambda_1$ or the third constraint in Eq.(7) becomes quickly negative. While in the case near-alignment limit $0.97 < \sin(\beta - \alpha) < 1$, which allows the vacuum stability to be fulfilled and $\Delta m$ can reach up to 280 GeV. This correlation between vacuum stability and $\sin(\beta - \alpha) \in [0.97, 1]$ is also observed in the case $\tan \beta = 10$ and is even more pronounced where one can see that $\Delta m$ can reach up to 600 GeV. The parameter space can be divided into two parts. The first region of parameter space is for light $H^\pm$. Once $m_{H^\pm} \sim m_{A^0}$, the mass splitting $\Delta m$ can be as large as 300 – 450 GeV. The second region is for heavy $H^\pm$. When $m_{H^\pm} \sim m_{H^0}$, the mass splitting $\Delta m$ can be extended to about 600 GeV for $\tan \beta = 10$. While in the case $\tan \beta = 5$, the maximum mass splitting $\Delta m$ is less than 200 GeV in the alignment limit $\sin(\beta - \alpha) = 1$, and could be extended to more than 250 GeV for $0.97 < \sin(\beta - \alpha) < 1$. We stress that even in the case where $\Delta m$ is rather small, the $T$ parameter severely constrains the charged Higgs mass to be less than about 200 GeV for $\tan \beta = 2.6, 5$ and 10.

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1 Here we assume the SM-like Higgs boson is the lightest CP-even scalar ($m_{H^0} > m_{h^0}$). For the reversed case $m_{H^0} = 125$ GeV and $m_{h^0} < m_{H^0}$, with another near alignment limit of $\cos(\beta - \alpha)$ one can also consider the similar process

$$pp \rightarrow W^\pm W^\pm \rightarrow jjH^\pm H^\pm \rightarrow jj(W^\pm h^0)(W^\pm h^0),$$

similar to this work.
FIG. 2. Branching fractions of the charged Higgs boson versus $m_{H^\pm}$ for type-I 2HDM with $m_{A^0} = 65$ GeV (upper-left panel), $m_{A^0} = 100$ GeV (upper-right panel) and for type-III 2HDM with $m_{A^0} = 65$ GeV (lower-left panel), $m_{A^0} = 100$ GeV (lower-right panel). The alignment limit $\sin(\beta - \alpha) = 1$ is assumed. Other modes like $t\bar{b}$ are omitted here for clarity.

### B. B physics constraints

The most severe constraints in flavor physics are due to the measurements of $B(B \to X_s\gamma)$, $B(B_{d,s} \to \mu^+\mu^-)$ and $\Delta m_s$ of $B$ mesons. For $B(B \to X_s\gamma)$, according to the latest analysis by [30], we have:

- In 2HDM type-II and IV, the $b \to s\gamma$ constraint forces the charged Higgs mass to be heavier than 580 GeV [30, 31] for any value of $\tan\beta \geq 1$.

- In 2HDM-I and III, charged Higgs with mass as low as $\sim 100 - 200$ GeV [30, 32] is still allowed as long as $\tan\beta \geq 2$.

For other B-physics observables we refer to the recent analysis [33], in which they also
FIG. 3. Branching fractions of the CP-odd Higgs boson $A^0$ versus $\tan\beta$ for $m_{A^0} = 65$ GeV in type-I 2HDM (left panel) and type-III 2HDM (right panel).

included $\Delta m_s$ and $B_{d,s} \rightarrow \mu^+\mu^-$. For a light charged Higgs boson, $100 < m_{H^\pm} < 200$ GeV, of interest in this study, one can conclude from [33] that $\tan\beta \geq 3$ is allowed for 2HDM type I and III.

C. $H^\pm$ and $A^0$ branching ratios and Direct searches

Before discussing the constraints coming from direct searches, we first show the branching ratios of $H^\pm$ and $A^0$ in both 2HDM type I and III in the following subsection. Calculations of these branching ratios are performed using the public code 2HDMC [34].

1. Branching ratios of $H^\pm$ and $A^0$

We illustrate in Fig. 2 the branching ratios of the charged Higgs boson both for 2HDM type I and III. It is clear that once the bosonic decay mode $H^\pm \rightarrow W^\pm A^0$ is open, it can be the dominant decay mode and both $B(H^+ \rightarrow t\bar{b})$ and $B(H^\pm \rightarrow \tau^\pm \nu_\tau)$ are highly suppressed.

In type I, one can see that the full dominance of the bosonic decay needs $\tan\beta > 5$ which reduces the $H^\pm \rightarrow \tau^\pm \nu_\tau$ and $H^\pm \rightarrow tb$ channels. The decay channel $H^\pm \rightarrow W^\pm h^0$ is vanishing because $H^\pm W^\mp h^0$ coupling is proportional to $\cos(\beta - \alpha) \approx 0$. In 2HDM type III, the coupling $H^\pm \tau^- \tau^+ \nu_\tau$ is proportional to $\tan\beta$ and since we assume that $\tan\beta \geq 2.5$, the $\tau\nu_\tau$ channel is slightly larger than in the 2HDM type I. It is clear from the lower panels of Fig. 2 that before $W^\pm A^0$ threshold, $H^\pm \rightarrow \tau^\pm \nu_\tau$ is the dominant decay mode and it is
amplified by taking large $\tan \beta$. In fact, such a large $\tan \beta$ not only enhances the $\tau \nu_\tau$ channel but also reduces $H^\pm \to cb, cs, tb$ modes, which are all proportional to $\cot \beta$. After crossing $W^\pm A^0$ threshold, $H^\pm \to W^\pm A^0$ becomes the dominant decay mode and taking large $\tan \beta$ can further suppress $H^\pm \to tb$ and makes $H^\pm \to W^\pm A^0$ even larger. Note that in the alignment limit $\cos(\beta - \alpha) = 0$, the coupling $H^\pm W^\mp h^0$ vanishes while $H^\pm W^\mp H^0$ is maximal and becomes similar to $H^\pm W^\mp A^0 = g/2$. Therefore, if $H^\pm \to W^\mp H^0$ is kinematically open it will compete on equal footing with $H^\pm \to W^\pm A^0$.

If $\tan \beta$ increases beyond 20 (45), the $\tau \nu$ mode could become comparable to the $WA$ mode for $m_{H^\pm} \gtrsim 200$ GeV and $m_{A^0} = 100$ (65) GeV in type III. In such a case, the model would be subject to the current charged Higgs searches via the $\tau \nu$ mode. In the following, we will concentrate on a scenario in which the $WA$ is the dominant mode.

The branching fractions for $A^0$ are depicted in Fig.3 as a function of $\tan \beta$ for $m_{A^0} = 65$ GeV in 2HDM type-I (left panel) and type III (right panel). In 2HDM type I, all couplings $A^0 ff$ are proportional to $\cot \beta$. Therefore, the $\tan \beta$ factorizes out in the branching ratio calculation leading to constant $B(A^0 \to b\bar{b}, \tau^+\tau^-, \mu^+\mu^-)$ as a function of $\tan \beta$. In the case of type III, the branching ratios $B(A^0 \to \tau^+\tau^-, \mu^+\mu^-)$ are enhanced for large $\tan \beta$ while $B(A^0 \to b\bar{b})$ is suppressed. Note for $m_{A^0} = 100$ GeV, none of $A^0 \to Z^* h^0$ and $A^0 \to W^* H^\pm$ are open, we observe similar behavior for $B(A^0 \to f \bar{f})$ in both type I and III.

2. LHC Constraint from $t \to bH^+ \to b\tau \nu_\tau$

For direct searches the LEP collaborations [5] had searched for charged Higgs pair production via the Drell-Yan process $e^+e^- \to Z/\gamma \to H^+H^-$, excluding $M_{H^\pm} < 80$ GeV (Type-II) and $M_{H^\pm} < 72.5$ GeV (Type-I) at 95% confidence level. The LHC collaborations also reported their charged Higgs search results for various mass regions. In the low mass region, the main decay mode is via $t \to bH^+$ followed by $H^\pm \to \tau^\pm \nu_\tau$ from CMS [10, 11] and ATLAS [7, 8]. In the high mass region, the main decay mode is $H^+ \to t\bar{b}$ from CMS[10, 15] and ATLAS[35].

When the charged Higgs mass is below $m_t - m_b$, it can be abundantly produced in top-quark decays, $t \to bH^+$, followed by charged Higgs decay $H^+ \to \tau^+ \nu_\tau$ or $H^+ \to W^+ A^0$. The CMS search for $t \to bH^+ \to b(\tau^+ \nu_\tau)$ [10–12] set limits on $B(t \to bH^+) \times B(H^+ \to \tau \nu_\tau)$. We rescale their limits to the type I and III 2HDM’s and show the exclusions in $(m_{H^\pm}, \tan \beta)$.
FIG. 4. Interpretation of CMS exclusion regions [10–12] in the 2HDM type I (left panel) and type III (right panel) projected on the plane of $(m_{H^\pm}, \tan \beta)$. The red points stand for the case the $WA$ mode is closed while the green and blue points are for the case that the $WA$ mode is open, with $m_{A^0} = 65$ and 35 GeV, respectively.

Plane. We note that in type I and III the decay width of $t \to bH^+$ scales as $\cot^2 \beta$:

$$\Gamma(t \to bH^+) = \frac{G_F |V_{tb}|^2}{8\sqrt{2}\pi} \lambda^{1/2} \left(1, \frac{m_b^2}{m_t^2}, \frac{m_{H^\pm}^2}{m_t^2}\right) \times \left[(m_t^2 + m_b^2)\cot^2 \beta(m_t^2 + m_b^2 - m_{H^\pm}^2) - 4m_t^2m_b^2\cot^2 \beta\right]. \quad (8)$$

where $\lambda^{1/2}(1, x^2, y^2) \equiv \sqrt{1 - (x + y)^2][1 - (x - y)^2]}$.

Interpretation of the CMS exclusion region [10–12] in the framework of 2HDM type I and III in $(\tan \beta, m_{H^\pm})$ plane is illustrated in Fig. 4 for both cases: $H^\pm \to W^\pm A^0$ closed and $H^\pm \to W^\pm A^0$ open. It is clear that for charged Higgs mass $\leq 120$ GeV with the $W^\pm A^0$ channel closed, $\tan \beta \leq 12$ is excluded. This exclusion is reduced for $m_{H^\pm} \geq 120$ GeV due to the fact that $B(H^+ \to \tau^+ \nu_\tau)$ is highly suppressed for 2HDM type I as $\tan \beta$ increases. On the other hand, when the $WA$ mode is open, the exclusion region in $(\tan \beta, m_{H^\pm})$ plane is significantly reduced in 2HDM type I. In the case of 2HDM type III, one can see from the right panel that $\tan \beta \leq 6$ is excluded for any value of charged Higgs mass provided that $H^\pm \to W^\pm A^0$ is closed. This limit on $\tan \beta$ is slightly more severe than what we can get from flavor physics (see the above discussion). When $H^\pm \to W^\pm A^0$ is open, either starting from $m_{H^\pm} \geq 115$ GeV for $m_{A^0} = 35$ GeV or $m_{H^\pm} \geq 145$ GeV for $m_{A^0} = 65$ GeV, $H^\pm \to \tau\nu_\tau$ mode is suppressed leading to no exclusion for any $\tan \beta$. Below the $W^\pm A^0$ threshold, $H^\pm \to \tau\nu_\tau$ channel is still the dominant one, one can see that the blue and green exclusions completely
fig. 5. Exclusions in the parameter space of \((m_{H^\pm}, \tan \beta)\) for type I (left panel) and for type III (right panel) 2HDM's obtained by rescaling the observed limits of the CMS results in Refs. [24] based on \(t \rightarrow bH^+ \rightarrow bW^+ A \rightarrow b(l^+ \nu_l)(\mu^+ \mu^-)\). overlap with the red one in 2HDM III.

\[\text{3. LHC Constraint from } t \rightarrow bH^+ \rightarrow bA^0 W^+ \rightarrow bW^+ \mu^+ \mu^-\]

Recently, the CMS collaboration [24] also reported the direct search for light charged Higgs via \(t \rightarrow bH^+ \rightarrow b(W^+ A^0) \rightarrow b(l^+ \nu_l)(\mu^+ \mu^-)\) with \(l = e, \mu\) [24] assuming that \(H^\pm\) decays 100% into \(W^\pm A^0\) and \(B(A^0 \rightarrow \mu^+ \mu^-) = 3 \times 10^{-4}\) and set a limit on \(B(t \rightarrow bH^+)\). We rescale the CMS limit and interpret it for 2HDM type I and III, which are depicted in Fig. 5. It is clear that the exclusion based on \(A^0 \rightarrow \mu^+ \mu^-\) also shows some differences between type I and III. It is easy to see from Fig. 3 that \(B(A^0 \rightarrow \mu^+ \mu^-)\) is only about \(2 \times 10^{-4}\) in type I but is as large as \(3 \times 10^{-3}\) in type III for \(\tan \beta > 3\). Therefore, the excluded region (blue shaded) in Fig. 5 for type III is much larger than that of type I.

In the rest of this work, we focus on type I and III 2HDM's, in which the charged Higgs mass is much less restricted. In addition, we also focus on the currently-allowed parameter space region where \(H^\pm\) decays dominantly into \(W^\pm A^0\) via VBF production of charged Higgs boson pair. This is complementary to the study in Ref. [25].
IV. SAME-SIGN CHARGED HIGGS PAIR PRODUCTION

A. The behavior of $pp \rightarrow H^\pm H^\pm j_F j_F$ process

Recently, the novel process of same-sign charged Higgs pair production was proposed in Ref. [25], and especially this process is very sensitive to the mass splitting $\Delta m \equiv m_{H^0} - m_{A^0}$ in the 2HDMs as it will be shown below. The cross section is enhanced according to the large mass splitting $\Delta m$. This process can be generated via the same-sign $W$ boson fusion, $pp \rightarrow W^\pm W^\pm j_F j_F \rightarrow H^\pm H^\pm j_F j_F$ at hadron colliders, where $j_F$ denotes the forward and energetic jet directly from the initial parton.

The relation between the mass splitting $\Delta m$ and same-sign charged Higgs pair production can be understood in the $2 \rightarrow 2$ subprocess $W^+ W^+ \rightarrow H^+ H^+$ at amplitude level. This subprocess is induced by three t-channel diagrams with $h^0, H^0$ and $A^0$ exchange. In the alignment limit, $\cos(\beta - \alpha) = 0$, which is favored by the current Higgs data, the scattering amplitude for $W^+(p_1)W^+(p_2) \rightarrow H^+(q_1)H^+(q_2)$ is only mediated by $H^0$ and $A^0$ and is given by

$$iM^{H^0+A^0} = ig^2q_1 \cdot \epsilon(p_1) q_2 \cdot \epsilon(p_2) \left[ \frac{1}{t - m_{A^0}^2} - \frac{1}{t - m_{H^0}^2} \right] + (q_1 \leftrightarrow q_2, t \leftrightarrow u) \quad (9)$$

where $t = (p_1 - q_1)^2$ and $u = (p_1 - q_2)^2$, and $\epsilon(p_{1,2})$ are the polarization 4-vector of the incoming $W^+$ bosons. In the approximation $m_{A^0} \approx m_{H^0}$, the amplitude reduces to

$$iM^{H^0+A^0} = -ig^2q_1 \cdot \epsilon(p_1) q_2 \cdot \epsilon(p_2) \frac{2m_{A^0}}{(t - m_{A^0}^2)^2} \Delta m + (q_1 \leftrightarrow q_2, t \leftrightarrow u) \quad (10)$$

It is clear to see that the amplitude is proportional to $\Delta m$ from the above formula with $m_{A^0} \approx m_{H^0}$.

We stress first that the production cross section $pp \rightarrow H^\pm H^\pm j_F j_F$ is the same for both 2HDM type I and III. Only the decay of the charged Higgs bosons that will make the process model dependent. The full signal process including decays of $H^\pm, W^\pm, A^0$ is given by

$$pp \rightarrow W^\pm W^\pm j_F j_F \rightarrow H^\pm H^\pm j_F j_F \rightarrow (W^\pm A^0)(W^\pm A^0)j_F j_F \rightarrow l^\pm \nu(b\bar{b})l^\pm \nu(b\bar{b})j_F j_F \quad (11)$$

in type-I 2HDM, and

$$pp \rightarrow W^\pm W^\pm j_F j_F \rightarrow H^\pm H^\pm j_F j_F \rightarrow (W^\pm A^0)(W^\pm A^0)j_F j_F \rightarrow l^\pm \nu(\tau^+ \tau^-)l^\pm \nu(\tau^+ \tau^-)j_F j_F \quad (12)$$
FIG. 6. The production cross sections of $pp \to H^+H^+j_Fj_F$ (solid line) and $pp \to H^-H^-j_Fj_F$ (dashed line) versus $m_{H^\pm}$ at $\sqrt{s} = 14$ TeV (left panel) and $\sqrt{s} = 27$ TeV (right panel), for $\Delta m = 100$ GeV (black), 200 GeV (blue), and 300 GeV (red). Notice the VBF cut $\eta_{j_1} \times \eta_{j_2} < 0$ and $|\Delta \eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair are applied.

in type-III 2HDM. We advocate that the novel signatures including the combination of a pair of same-sign dileptons ($l^\pm l'^\pm$), a forward and energetic jet pair ($j_Fj_F$), and two pairs of bottom quarks ($b\bar{b}$) or tau leptons ($\tau^+\tau^-$) coming from two light pseudoscalars $A^0$ can largely reduce the possible SM backgrounds.

We believe if this kind of signature is discovered and production cross section is measured in the near future, we can almost pin down the mass spectrum of these new scalar bosons in the type-I or type-III 2HDM. On the other hand, even the LHC collaborations do not find any positive result from this process at the end, we would still gain deeper understanding about what kind of scalar mass spectrum may not be possible in the 2HDMs. All in all, this process will become important and win-win situation for the future charged Higgs searches at the LHC.

As indicated by Eq. (10) the production cross section of $pp \to H^\pm H^\pm j_Fj_F$ scales as the square of the mass splitting $\Delta m$. We quantitatively show this relation by plotting the production cross sections versus $m_{H^\pm}$ in Fig.6 with $\Delta m = 100$, 200, and 300 GeV at $\sqrt{s} = 14$ TeV (left panel) and $\sqrt{s} = 27$ TeV (right panel). It is clear to observe that the cross section is enhanced according to the large mass splitting $\Delta m$. Note that we have used the general Two-Higgs-Doublet Model UFO model file [40] and employ Madgraph5 aMC@NLO [41] with VBF cut $\eta_{j_1} \times \eta_{j_2} < 0$ and $|\Delta \eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair to evaluate the cross sections. Furthermore, in order to study the effects
TABLE II. Sum of cross sections for $\sigma(pp \rightarrow H^+H^-j_Fj_F)$ and $\sigma(pp \rightarrow H^-H^+j_Fj_F)$ [fb] at $\sqrt{s} = 14$ TeV for $\sin(\beta - \alpha) = 1, 0.95, 0.9$ with the benchmark points $\Delta m = 100, 200, 300$ GeV and $m_{H^\pm} = 100, 200, 300$ GeV. Notice the VBF cut $\eta_{j1} \times \eta_{j2} < 0$ and $|\Delta \eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair have been applied.

| $\Delta m$ (GeV) | $m_{H^\pm}$ (GeV) | $\sin(\beta - \alpha) = 1$ | $\sin(\beta - \alpha) = 0.95$ | $\sin(\beta - \alpha) = 0.9$ |
|------------------|------------------|------------------|------------------|------------------|
| 100              | 100              | $5.84 \times 10^{-1}$  | $5.43 \times 10^{-1}$  | $5.03 \times 10^{-1}$  |
| 100              | 200              | $2.30 \times 10^{-1}$  | $2.11 \times 10^{-1}$  | $1.95 \times 10^{-1}$  |
| 100              | 300              | $8.57 \times 10^{-2}$  | $7.86 \times 10^{-2}$  | $7.21 \times 10^{-2}$  |
| 200              | 100              | $1.81$               | $1.59$               | $1.39$               |
| 200              | 200              | $8.82 \times 10^{-1}$  | $7.66 \times 10^{-1}$  | $6.62 \times 10^{-1}$  |
| 200              | 300              | $3.85 \times 10^{-1}$  | $3.33 \times 10^{-1}$  | $2.85 \times 10^{-1}$  |
| 300              | 100              | $3.14$               | $2.70$               | $2.32$               |
| 300              | 200              | $1.75$               | $1.49$               | $1.26$               |
| 300              | 300              | $8.54 \times 10^{-1}$  | $7.21 \times 10^{-1}$  | $6.05 \times 10^{-1}$  |

of the near-alignment limit on the production cross sections, we list some benchmark points for the relation of cross sections with $\sin(\beta - \alpha) = 1, 0.95, 0.9$ in Table II at $\sqrt{s} = 14$ TeV and Table III at $\sqrt{s} = 27$ TeV, respectively.

B. Signal-background analysis for Type-I 2HDM

The signal process in Eq. (11) is unique with a signature including the combination of a pair of same-sign dileptons ($l^\pm l^\pm$), a pair of forward and energetic jets ($j_Fj_F$), and two pairs of bottom quarks ($b\bar{b}$) coming from two light pseudoscalar $A^0$. There are a few SM backgrounds that can mimic this kind of final states. We consider the following four processes as the main SM backgrounds,

$$pp \rightarrow t\bar{t}t\bar{t} \rightarrow (bW^+)(\bar{b}W^-)(bW^+)(\bar{b}W^-) \rightarrow l^\pm l^\pm 4b4j, \quad (13)$$

$$pp \rightarrow t\bar{t}bbl^+l^- \rightarrow (bW^+)\bar{b}(\bar{b}W^-)bl^+l^- \rightarrow l^\pm l^\pm l^- 4b2j, \quad (14)$$
TABLE III. Sum of cross sections for $\sigma(pp \to H^+H^+_Fj_F)$ and $\sigma(pp \to H^-H^-_Fj_F)$ [fb] at $\sqrt{s} = 27$ TeV for $\sin(\beta - \alpha) = 1, 0.95, 0.9$ with the benchmark points $\Delta m = 100, 200, 300$ GeV and $m_{H^\pm} = 100, 200, 300$ GeV. Notice the VBF cut $\eta_{j_1} \times \eta_{j_2} < 0$ and $|\Delta \eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair have been applied.

| $\Delta m$ (GeV) | $m_{H^\pm}$ (GeV) | $\sin(\beta - \alpha) = 1$ | $\sin(\beta - \alpha) = 0.95$ | $\sin(\beta - \alpha) = 0.9$ |
|------------------|------------------|-----------------|-----------------|-----------------|
| 100              | 1.64             | 1.52            | 1.41            |
| 100              | $7.46 \times 10^{-1}$ | $6.87 \times 10^{-1}$ | $6.34 \times 10^{-1}$ |
| 300              | $3.26 \times 10^{-1}$ | $2.99 \times 10^{-1}$ | $2.75 \times 10^{-1}$ |
| 100              | 5.24             | 4.59            | 4.00            |
| 200              | 2.91             | 2.53            | 2.18            |
| 300              | 1.47             | 1.27            | 1.09            |
| 100              | 9.35             | 8.04            | 6.87            |
| 300              | 5.84             | 4.97            | 4.20            |
| 300              | 3.29             | 2.77            | 2.33            |

$pp \to t\bar{t}b \to (bW^+)(\bar{b}W^-)(bW^+)\bar{b} \to l^+l^-4b2j$

or

$pp \to t\bar{t}b \to (bW^+)(\bar{b}W^-)b \to l^-l^-4b2j$.  \(15\)

$pp \to t\bar{t}bbjj \to (bW^+)(bW^+)bbjj \to l^+l^-4b2j$

or

$pp \to t\bar{t}bbjj \to (\bar{b}W^-)(\bar{b}W^-)bbjj \to l^-l^-4b2j$.  \(16\)

All signal and SM background events are simulated at leading order (LO) using Madgraph5 aMC@NLO \cite{madgraph}. 2 In the following, we choose $m_{H^\pm} = 205$ GeV and $m_{A^0} = 65$ GeV to illustrate the cut flow under a sequence of selection cuts at $\sqrt{s} = 14$ TeV.

1. We first identify the forward jet pair $(j_F.j_F)$ in the VBF-type process and apply the VBF cut $\eta_{j_1} \times \eta_{j_2} < 0$ and $|\Delta \eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair in Madgraph5 aMC@NLO at parton level for all signal and

2 The NLO QCD corrections for the signal process in Eq. (11) and background processes in Eq. (13) and (14) have been checked with Madgraph5 aMC@NLO. We assume that the kinematic distributions are only mildly affected by these higher order QCD effects.
TABLE IV. Cut flow table for the Type-I 2HDM signal $pp \rightarrow H^\pm H^\pm jFjF$ with $m_{H^\pm} = 205$ GeV, $m_{A^0} = 65$ GeV, $\Delta m = 200$ GeV, $\tan \beta = 5$ and $\sin(\beta - \alpha) = 0.97$, and various backgrounds at $\sqrt{s} = 14$ TeV.

| Cross section (fb) | signal | $t\bar{t}t\bar{t}$ | $t\bar{t}b\bar{b}l^+l^-$ | $3t1b$ | $2t2b2j$ |
|-------------------|--------|--------------------|--------------------------|--------|----------|
| Preselection      | $2.07 \times 10^{-2}$ | $4.94 \times 10^{-2}$ | $1.08 \times 10^{-2}$ | $7.74 \times 10^{-5}$ | $8.29 \times 10^{-5}$ |
| $N(b, l^\pm) \geq 3, 2$ |        |                    |                          |        |          |
| $P_T^{b,l^\pm} > 20$ GeV, $|\eta^{b,l}| < 2.5$ | $1.76 \times 10^{-3}$ | $6.17 \times 10^{-3}$ | $9.56 \times 10^{-4}$ | $9.57 \times 10^{-6}$ | $9.81 \times 10^{-6}$ |
| $N(j) \geq 2$ |        |                    |                          |        |          |
| $P_T^j > 30$ GeV, $m_{jj} > 500$ GeV | $1.46 \times 10^{-3}$ | $5.15 \times 10^{-3}$ | $4.18 \times 10^{-4}$ | $2.88 \times 10^{-6}$ | $4.05 \times 10^{-6}$ |
| $m_{H^\pm}$ Cuts |        |                    |                          |        |          |
| $M_{bb^\pm} < 250$ GeV | $1.41 \times 10^{-3}$ | $3.50 \times 10^{-3}$ | $2.71 \times 10^{-4}$ | $1.85 \times 10^{-6}$ | $2.62 \times 10^{-6}$ |
| $m_A$ Cuts |        |                    |                          |        |          |
| $50 < M_{bb^\pm} < 90$ GeV | $1.30 \times 10^{-3}$ | $1.68 \times 10^{-3}$ | $1.61 \times 10^{-4}$ | $7.58 \times 10^{-7}$ | $1.14 \times 10^{-6}$ |

SM background events. The cross sections for both signal and background events after this pre-selection cut are shown in the first row of Table IV.

2. Then we employ **Pythia8** [42] for parton showering and hadronization. **Delphes3** [43] with default settings is used for fast detector simulation. Finally, all events are analyzed with **MadAnalysis5** [44]. We require to see a pair of same-sign dileptons ($l^\pm l^\pm$) and at least 3$b$ in the event as the trigger with the following sequence of event selection cuts

$$N(b, l^\pm) \geq 3, 2, \quad P_T^{l^\pm} > 20 \text{ GeV}, \quad |\eta^{l^\pm}| < 2.5, \quad P_T^{b} > 20 \text{ GeV}, \quad |\eta^{b}| < 2.5.$$ (17)

The cross sections for both signal and background events are shown in the second row of Table IV.

3. The forward jet pair is also required to be energetic with the following selection cuts

$$N(j) \geq 2, \quad p_T^{j} > 30 \text{ GeV}, \quad |\eta^{j}| < 5, \quad m_{jj} > 500 \text{ GeV}.$$ (18)

The cross sections after this step for both signal and background events are shown in the third row of Table IV.
FIG. 7. Invariant mass distributions of $M_{bb\ell\ell}$ (left panel) and $M_{bb}$ (right panel) for the signal with $m_{H^\pm} = 205$ GeV, $m_{A^0} = 65$ GeV, $\Delta m = 200$ GeV, $\tan \beta = 5$ and $\sin(\beta - \alpha) = 0.97$, and the total background at $\sqrt{s} = 14$ TeV. Preselection cuts in Eqs. (17) and (18) are imposed.

4. The kinematical distributions of $M_{bb\ell\ell}$ and $M_{bb}$ with $m_{H^\pm} = 205$ GeV and $m_{A^0} = 65$ GeV for the signal and backgrounds are shown in Fig.7. Note that we have applied all the selection cuts except for $m_{H^\pm}$ and $m_{A^0}$ cuts in these two kinematical distributions. The signal distribution of $M_{bb\ell\ell}$ tends to concentrate in the region of $M_{bb\ell\ell} < 250$ GeV and decreases more rapidly toward the higher $M_{bb\ell\ell}$. On the other hand, the background is relatively flat after 150 GeV to 500 GeV. It is also clear to observe the peak shape at 65 GeV in $M_{bb}$ distribution for the signal from the resonance of $A^0$. These two behaviors can help us to distinguish between the signal and the background.

5. Finally, in order to further reduce the contributions from SM backgrounds, the following selection cuts are imposed on both signal and background events. For $m_{H^\pm}$ cuts at least two bottom quarks and a lepton have to satisfy

$$M_{bb\ell\ell} \leq M_{H^\pm} + 45 \text{ GeV}. \quad (19)$$

For $m_{A^0}$ cuts at least a pair of bottom quarks is required to around the mass of $A^0$:

$$m_{A^0} - 15 \text{ GeV} \leq M_{bb} \leq m_{A^0} + 25 \text{ GeV}. \quad (20)$$

Again, the cross sections for both signal and background events after this sequence of event selection cuts are shown in the last two rows of Table IV.

After all selection cuts the signal-to-background ratio is almost close to 1. With a luminosity of 3000 fb$^{-1}$ we expect about 4 signal and 5 background events. The major background comes from $t\bar{t}t\bar{t}$ production while the other backgrounds listed in Table IV are much suppressed.
TABLE V. Cut flow table for the Type-I 2HDM signal $pp \rightarrow H^\pm H^\pm j_F j_F$ with $m_{H^\pm} = 205$ GeV, $m_{A^0} = 65$ GeV, $\Delta m = 200$ GeV, $\tan \beta = 5$ and $\sin(\beta - \alpha) = 0.97$, and various backgrounds at $\sqrt{s} = 27$ TeV.

| Cross section (fb) | signal | $tt\bar{t}\bar{t}$ | $ttb\bar{b}l^+l^-$ | 3$t1b$ | 2t2b2j |
|-------------------|--------|-----------------|-----------------|--------|--------|
| Preselection      | $6.88 \times 10^{-2}$ | $5.67 \times 10^{-1}$ | $5.60 \times 10^{-2}$ | $2.40 \times 10^{-4}$ | $6.76 \times 10^{-4}$ |
| $N(b, l^\pm) \geq 3, 2,$ | $5.15 \times 10^{-3}$ | $5.67 \times 10^{-2}$ | $4.43 \times 10^{-3}$ | $2.44 \times 10^{-5}$ | $6.42 \times 10^{-5}$ |
| $P_T^{b,l^\pm} > 20$GeV, $|\eta_{b,l^\pm}| < 2.5$ | $4.54 \times 10^{-3}$ | $5.22 \times 10^{-2}$ | $2.49 \times 10^{-3}$ | $9.67 \times 10^{-6}$ | $3.27 \times 10^{-5}$ |
| $m_{H^\pm}$ Cuts | $M_{bbl^\pm} < 200$GeV | $4.10 \times 10^{-3}$ | $2.28 \times 10^{-2}$ | $1.08 \times 10^{-3}$ | $4.29 \times 10^{-6}$ |
| $m_{A^0}$ Cuts | $|M_{bb} - m_{A^0}| \leq 15$GeV | $3.76 \times 10^{-3}$ | $1.12 \times 10^{-2}$ | $6.09 \times 10^{-4}$ | $1.91 \times 10^{-6}$ |

We further extend the signal-background analysis to the proposed 27 TeV $pp$ collider (HE-LHC). Since the SM background cross sections grow faster than the signal one from $\sqrt{s} = 14$ to 27 TeV. In order to reduce the enhanced background cross sections, both $m_{H^\pm}$ and $m_{A^0}$ cuts are tightened relative to those Eqs. (19) and (20). For $m_{H^\pm}$ cuts at least two bottom quarks and a lepton have to satisfy

$$M_{bbl^\pm} \leq M_{H^\pm} - 5 \text{ GeV}. \quad (21)$$

For $m_{A^0}$ cuts at least a pair of bottom quarks is required to be around the mass of $A^0$:

$$|M_{bb} - m_{A^0}| \leq 15 \text{ GeV}. \quad (22)$$

Other preselection cuts, given in Eqs. (17), (18), are the same as before. On the other hand, the shape of kinematical distributions for $M_{bbl^\pm}$ and $M_{bb}$ with $m_{H^\pm} = 205$ GeV and $m_{A^0} = 65$ GeV at $\sqrt{s} = 27$ TeV for the signal and backgrounds are similar to Fig.7, so we will not repeat to display them here. We choose the same signal benchmark point to illustrate the cut flow under a sequence of selection cuts at $\sqrt{s} = 27$ TeV in Table V.

Finally, we summarize our signal-background analysis for Type-I 2HDM at $\sqrt{s} = 27$ TeV with luminosity $\mathcal{L} = 15$ab$^{-1}$ in Fig.8. The preselection cuts in Eqs. (17), (18), (21) and (22)
FIG. 8. The significance $Z$ versus $m_{A^0}$ from 30 to 100 GeV in Type-I 2HDM at $\sqrt{s} = 27$ TeV with luminosity $\mathcal{L} = 15$ ab$^{-1}$. We have fixed $\sin(\beta - \alpha) = 1$ and $\tan \beta = 5$ with $\Delta m \equiv m_{H^0} - m_{A^0} = 100$ GeV (upper-left panel), 200 GeV (upper-right panel), and 250 GeV (lower panel) are imposed as before. We vary $m_{A^0}$ from 30 to 100 GeV with fixed $\sin(\beta - \alpha) = 1$ and $\tan \beta = 5$\(^3\) for $\Delta m = m_{H^0} - m_{A^0} = 100$ GeV (upper-left panel), 200 GeV (upper-right panel), and 250 GeV (lower panel) in Fig.8. The black lines are $m_{H^\pm} = m_{H^0}$, the blue lines are $m_{H^\pm} = m_{H^0} - 15$ GeV, and the red lines are $m_{H^\pm} = m_{H^0} + 15$ GeV. We first define the significance by

$$Z = \sqrt{2 \cdot \left[ (s + b) \cdot \ln(1 + s/b) - s \right]} ,$$

where $s$ and $b$ represent the numbers of signal and background events, respectively. According to the production cross sections of same-sign charged Higgs in the right panel of Fig.6, it is obvious that the cases with small mass splitting $\Delta m$ are difficult to be detected even at \(^3\) For the effect on the significance from $\sin(\beta - \alpha)$ near the alignment limit and various $\tan \beta$ values can be referred to Table III and Fig.2,3, respectively.
HE-LHC with high luminosity. The maximum significance is only about $Z = 1.2$ for $\Delta m = 100$ GeV. We need other charged Higgs production channels to detect this kind of small mass splitting $\Delta m$ cases. However, this same-sign charged Higgs production channel is sensitive to the cases with large mass splitting $\Delta m$. The average significance is about $Z = 3$ for $m_{A^0}$ from 30 GeV to 100 GeV with $\Delta m = 200$ GeV, and its maximum can reach to more than $Z = 5$ at $m_{A^0} = 40$ GeV. Moreover, the average significance can grow to about $Z = 4$ for $m_{A^0}$ from 30 GeV to 100 GeV with $\Delta m = 250$ GeV, and its maximum can further reach to $Z = 5.8$ at $m_{A^0} = 60$ GeV.

C. Signal-background analysis for Type-III 2HDM

In type III 2HDM, the major decay of the pseudoscalar $A^0$ is $A^0 \to \tau \tau$. Therefore, we modify the above signal-background analysis to two pairs of tau leptons, instead of two pairs of bottom quarks, in the final state. The decay chain is shown in Eq. (12). Therefore, we are considering the following set of backgrounds at LO:

\begin{align}
pp \to t\bar{t}Zjj &\to (bW^+)(\bar{b}W^-)(\tau^+\tau^-)jj \to l^\pm 2b3\tau 2j, \\
p p \to t\bar{t}W^\pm jj &\to (bW^+)\bar{b}(W^-)(\tau^\pm\nu_\tau)jj \to l^\pm 2b2\tau 2j, \\
p p \to W^\pm W^\mp Zjj &\to (l^\pm\nu_l)(\tau^\pm\nu_\tau)(\tau^\mp\tau^-)jj \to l^\pm 3\tau 2j, \\
p p \to W^\pm ZZjj &\to (l^\pm\nu_l)(\tau^+\tau^-)(\tau^+\tau^-)jj \to l^\pm 4\tau 2j.
\end{align}

The extra same-sign charged leptons may come from some cascade decays of the tau leptons, B mesons, or showering. Similarly, the extra tau leptons can also come from B mesons cascade decays, showering, or jet misidentification.

Again, we choose $m_{H^\pm} = 205$ GeV and $m_{A^0} = 65$ GeV to illustrate the cut flow under a sequence of selection cuts.

1. We apply the same VBF cut $\eta_{j_1} \times \eta_{j_2} < 0$ and $|\Delta\eta_{jj}| > 2.5$ for the minimum rapidity difference between the forward jet pair at parton level for all signal and SM background events. Their cross sections after this pre-selection cut are shown in the first row of Table VI.
The cross sections for both signal and backgrounds are shown in the second row of Table VI.

3. The forward jet pair is also required to be energetic with the following selection cuts

\[ N(j) > 2, \quad p_T^j > 30 \text{ GeV}, \quad |\eta^j| < 5, \quad m_{jj} > 500 \text{ GeV}. \]  

The cross sections after this step for both signal and backgrounds are shown in the third row of Table VI.

4. Since the major background comes from the $t\bar{t}$ associated processes, we apply b-jet veto to suppress background events:

\[ N(b) = 0 \quad \text{with} \quad P_T^b > 20 \text{ GeV}, \quad |\eta^b| < 2.5 \]  

2. After parton showering and hadronization with Pythia8 and detector simulation by Delphes3, we apply the selections cuts for a pair of same-sign dileptons and at least 3τ:

\[ N(\tau, l^{\pm}) \geq 3, 2, \quad P_T^{l^{\pm}} > 20 \text{ GeV}, \quad |\eta^{l^{\pm}}| < 2.5, \quad P_T^\tau > 20 \text{ GeV}, \quad |\eta^\tau| < 2.5. \] (28)

The cross sections for both signal and backgrounds are shown in the second row of Table VI.

| Cross section (fb) | signal | $t\bar{t}Zjj$ | $t\bar{t}W^{\pm}jj$ | $W^{\pm}W^{\mp}Zjj$ | $W^{\pm}ZZjj$ |
|-------------------|--------|--------------|----------------|----------------|----------------|
| Preselection      | $2.98 \times 10^{-2}$ | $3.60 \times 10^{-1}$ | $2.44 \times 10^{-1}$ | $3.28 \times 10^{-2}$ | $1.87 \times 10^{-3}$ |
| $N(\tau, l^{\pm}) \geq 3, 2,$ | $1.23 \times 10^{-3}$ | $7.42 \times 10^{-3}$ | $1.07 \times 10^{-3}$ | $3.89 \times 10^{-4}$ | $9.61 \times 10^{-5}$ |
| $P_T^{l^{\pm}} > 20 \text{ GeV}, |\eta^{l^{\pm}}| < 2.5$ | $9.81 \times 10^{-4}$ | $4.63 \times 10^{-3}$ | $6.19 \times 10^{-4}$ | $1.97 \times 10^{-4}$ | $5.08 \times 10^{-5}$ |
| $N(j) \geq 2,$ | $9.15 \times 10^{-4}$ | $1.15 \times 10^{-3}$ | $2.03 \times 10^{-4}$ | $1.71 \times 10^{-4}$ | $4.32 \times 10^{-5}$ |
| $p_T^j > 30 \text{ GeV}, m_{jj} > 500 \text{ GeV}$ | $8.24 \times 10^{-4}$ | $7.52 \times 10^{-4}$ | $9.18 \times 10^{-5}$ | $1.15 \times 10^{-4}$ | $2.98 \times 10^{-5}$ |
| $m_{H^{\pm}} \text{ Cut}$ | $7.95 \times 10^{-4}$ | $6.28 \times 10^{-4}$ | $5.81 \times 10^{-5}$ | $1.04 \times 10^{-4}$ | $2.73 \times 10^{-5}$ |
| $M_{\tau+\tau-} < 250 \text{ GeV}$ | $6.24 \times 10^{-4}$ | $7.52 \times 10^{-4}$ | $9.18 \times 10^{-5}$ | $1.15 \times 10^{-4}$ | $2.98 \times 10^{-5}$ |
| $m_{A^0} \text{ Cut}$ | $40 < M_{\tau+\tau-} < 100 \text{ GeV}$ | $7.95 \times 10^{-4}$ | $6.28 \times 10^{-4}$ | $5.81 \times 10^{-5}$ | $1.04 \times 10^{-4}$ | $2.73 \times 10^{-5}$ |
FIG. 9. Invariant mass distributions of $M_{l^\pm \tau^+ \tau^-}$ (left panel) and $M_{\tau^+ \tau^-}$ (right panel) for the signal with $m_{H^\pm} = 205$ GeV, $m_{A^0} = 65$ GeV, $\Delta m = 200$ GeV, $\tan \beta = 5$ and $\sin(\beta - \alpha) = 0.97$, and the total background at $\sqrt{s} = 14$ TeV. Preselection cuts in Eqs. (28), (29) and (30) are imposed.

The cross sections after this step for both signal and background events are shown in the fourth row of Table VI.

5. The kinematical distributions of $M_{l^\pm \tau^+ \tau^-}$ and $M_{\tau^+ \tau^-}$ with $m_{H^\pm} = 205$ GeV and $m_{A^0} = 65$ GeV for the signal and backgrounds are shown in Fig.9. Note that we have applied all the selection cuts except for $m_{H^\pm}$ and $m_{A^0}$ cuts in these two kinematical distributions. The signal and background distributions of $M_{l^\pm \tau^+ \tau^-}$ are similar to $M_{bb}$ in Fig.7. However, the peak shape at 65 GeV in $M_{\tau^+ \tau^-}$ distribution for the signal from the resonance of $A^0$ is not so obvious compared with $M_{bb}$ distribution in Fig.7. The reason is that the $\tau$-tagging is not as effective as $b$-tagging. On the other hand, since there are always neutrinos in $\tau$ lepton decays, the $\tau$ lepton cannot be fully reconstructed. This also explains why the shift of fat peak shape from 65 GeV to a slightly lower $M_{\tau^+ \tau^-}$.

6. Finally, in order to further reduce the contributions from SM backgrounds, the following selection cuts are imposed on both signal and background events. For $m_{H^\pm}$ cuts at least two opposite-sign tau leptons and a lepton have to satisfy

$$M_{l^\pm \tau^+ \tau^-} \leq m_{H^\pm} + 45 \text{ GeV.}$$

(31)

For the $m_{A^0}$ cut at least a pair of opposite-sign tau leptons is required to around the mass of $A^0$:

$$m_{A^0} - 25 \text{ GeV} \leq M_{\tau^+ \tau^-} \leq m_{A^0} + 35 \text{ GeV.}$$

(32)
TABLE VII. Cut flow table for the Type-III 2HDM signal $pp \rightarrow H^\pm H^\mp jFjF$ with $m_{H^\pm} = 205$ GeV, $m_{A_0} = 65$ GeV, $\Delta m = 200$ GeV, $\tan \beta = 5$ and $\sin(\beta - \alpha) = 0.97$, and various backgrounds at $\sqrt{s} = 27$ TeV.

| Cross section (fb) | signal | $t\bar{t}Zjj$ | $t\bar{t}W^\pm jj$ | $W^\pm W^\mp Zjj$ | $W^\pm ZZjj$ |
|-------------------|--------|---------------|-------------------|-------------------|----------------|
| Preselection      |        |               |                   |                   |                |
| $N(\tau, l^\pm) \geq 3, 2$, | $4.27 \times 10^{-3}$ | $3.71 \times 10^{-3}$ | $2.75 \times 10^{-3}$ | $2.35 \times 10^{-3}$ | $2.51 \times 10^{-3}$ | $2.20 \times 10^{-3}$ |
| $P_T^{T^\pm} > 20$ GeV, $|\eta^T|^\tau < 2.5$, | $4.96 \times 10^{-2}$ | $3.69 \times 10^{-2}$ | $4.04 \times 10^{-3}$ | $2.20 \times 10^{-3}$ | $1.96 \times 10^{-4}$ | $1.96 \times 10^{-4}$ |
| $N(j) \geq 2$, | $6.14 \times 10^{-3}$ | $4.50 \times 10^{-3}$ | $4.17 \times 10^{-4}$ | $2.29 \times 10^{-4}$ | $2.29 \times 10^{-4}$ | $2.19 \times 10^{-4}$ |
| $P_T^j > 30$ GeV, $M_{jj} > 500$ GeV, | $1.51 \times 10^{-1}$ | $1.08 \times 10^{-3}$ | $3.94 \times 10^{-4}$ | $6.63 \times 10^{-5}$ | $8.62 \times 10^{-3}$ | $6.63 \times 10^{-5}$ |
| b-jet veto | $9.39 \times 10^{-2}$ | $9.23 \times 10^{-3}$ | $1.41 \times 10^{-3}$ | $9.23 \times 10^{-4}$ | $2.19 \times 10^{-4}$ | $9.23 \times 10^{-4}$ |
| $m_{H^\pm}$ Cut | $1.51 \times 10^{-1}$ | $1.08 \times 10^{-3}$ | $3.94 \times 10^{-4}$ | $6.63 \times 10^{-5}$ | $8.62 \times 10^{-3}$ | $6.63 \times 10^{-5}$ |
| $M_{\tau^+ \tau^-} < 200$ GeV | $2.75 \times 10^{-3}$ | $4.04 \times 10^{-3}$ | $4.17 \times 10^{-4}$ | $3.94 \times 10^{-4}$ | $1.09 \times 10^{-4}$ | $3.94 \times 10^{-4}$ |
| $m_{A_0}$ Cut | $2.35 \times 10^{-3}$ | $2.20 \times 10^{-3}$ | $1.96 \times 10^{-4}$ | $2.29 \times 10^{-4}$ | $6.63 \times 10^{-5}$ | $2.29 \times 10^{-4}$ |
| $40 < M_{\tau^+ \tau^-} < 70$ GeV | $2.75 \times 10^{-3}$ | $4.04 \times 10^{-3}$ | $4.17 \times 10^{-4}$ | $3.94 \times 10^{-4}$ | $1.09 \times 10^{-4}$ | $3.94 \times 10^{-4}$ |

Again, the cross sections for both signal and background events after this sequence of event selection cuts are shown in the last two rows of Table VI.

We further extend the signal-background analysis to the proposed 27 TeV $pp$ collider (HE-LHC). Similar as before, we tighten both $m_{H^\pm}$ and $m_{A_0}$ cuts relative to those in Eqs. (31) and (32). For $m_{H^\pm}$ cuts at least two tau leptons and a lepton have to satisfy

$$M_{bl\bar{l}} \leq M_{H^\pm} - 5 \text{ GeV.}$$

(33)

For $m_{A_0}$ cuts at least a pair of opposite-sign tau leptons is required to around the mass of $A^0$:

$$m_{A_0} - 25 \text{ GeV} \leq M_{\tau^+ \tau^-} \leq m_{A_0} + 5 \text{ GeV.}$$

(34)

Other preselection cuts in Eqs. (28), (29) and (30) are imposed, as before. We choose the same signal benchmark point to illustrate the cut flow under a sequence of selection cuts at $\sqrt{s} = 27$ TeV in Table VII.

4 Here we apply an asymmetric mass window cut for $M_{\tau^+ \tau^-}$ based on the shift of peak shape in the right panel of Fig.9 and in order to veto the pair of opposite-sign tau leptons from the Z-pole.
Finally, we summarize the results for signal-background analysis of Type-III 2HDM at $\sqrt{s} = 27$ TeV with luminosity $\mathcal{L} = 15 ab^{-1}$ in Fig.10. The preselection cuts in Eqs. (28), (29), (33) and (34) are imposed as before. We vary $m_{A^0}$ from 30 to 100 GeV with fixed $\sin(\beta-\alpha)=1$ and $\tan\beta=5$ for $\Delta m = m_{H^0} - m_{A^0} = 100$ GeV (upper-left panel), 200 GeV (upper-right panel), and 250 GeV (lower panel) in Fig.10. The black lines are $m_{H^\pm} = m_{H^0}$, the blue lines are $m_{H^\pm} = m_{H^0} - 15$ GeV, and the red lines are $m_{H^\pm} = m_{H^0} + 15$ GeV. The maximum significance can reach to about $Z = 1.7$ at $m_{A^0} = 80$ GeV for $\Delta m = 100$ GeV. Notice that the mass spectrum with $\Delta m = 100$ GeV and $m_{H^\pm} = m_{H^0} - 15$ GeV in Type-III 2HDM will produce sizable $B(H^\pm \rightarrow \tau\nu_\tau)$ and suppress $B(H^\pm \rightarrow W^\pm A^0)$. That makes reductions of the significance for the blue line in the upper-left panel in Fig.10. On the other hand, the significance can reach to more than $Z = 3$ for $m_{A^0}$ from 30 GeV to 100 GeV with $\Delta m = 200$ GeV, and its maximum is about $Z = 5.2$ in $m_{A^0} = 40-50$ GeV. Moreover, the average significance can grow to more than $Z = 4$ for $m_{A^0}$ from 30 GeV to 100 GeV with $\Delta m = 250$ GeV, and its maximum can further reach to almost $Z = 6$ at
$m_{A^0} = 50$ GeV.

V. CONCLUSIONS

Extending the minimal Higgs sector is one of the ways to address some weakness of the SM. Such extensions can give rise to rich phenomenology. The 2HDM is one of the most popular extended models in literature. Exploring the whole mass spectrum in 2HDM is undoubtedly an important mission to help us understand the mystery of electroweak symmetry breaking. There are only a few examples that can cover the effects of all new scalar masses in a single process. We have studied a novel process – production of same-sign charged Higgs production shown in Eq. (1), which was first proposed in Ref. [25]. It allows one to probe the whole mass spectrum in the 2HDM for some specific mass relations.

We have investigated same-sign charged Higgs-boson production via vector-boson-fusion at the HL-LHC and HE-LHC (27 TeV) in Type I and III 2HDM’s. We have investigated the dependence of the production cross section on the mass difference $\Delta m \equiv m_{H^0} - m_{A^0}$ between the heavier scalar boson $H^0$ and the pseudoscalar boson $A^0$. In the approximation $m_{H^0} \approx m_{A^0}$, the scattering amplitude of the key subprocess $W^+W^+ \rightarrow H^+H^+$ is proportional to $\Delta m$, such that the production cross section nearly vanishes in the limit $\Delta m \rightarrow 0$. As we mentioned before, the measurement of the production cross section is a good way to understand the mass spectrum of the heavier scalar boson and the pseudoscalar boson.

Given the constraints from electroweak precision, B physics, and direct searches at colliders, we have explored the allowed parameter space in $m_{H^+}$, $\tan \beta$, $\Delta m$. Then we investigated the sensitivity to the allowed parameter space at the HL-LHC and HE-LHC, especially we have made use of the bosonic channel $W^\pm A^0$ of the charged Higgs boson, which is complementary to the study in Ref. [25].

In type I 2HDM, we used the decay channel $H^\pm H^\pm \rightarrow (W^\pm A^0)(W^\pm A^0) \rightarrow (l^\pm \nu b\bar{b}) (l^\pm \nu b\bar{b})$ together with a pair of forward jets to perform the signal-background analysis. At the end, we found about 4 signal events versus 5 background events at HL-LHC with luminosity of 3000 fb$^{-1}$ for a typical benchmark point. At the HE-LHC, significance level of 2 – 5 can be achieved for $\Delta m = 200 – 250$ GeV.

On the other hand, in type III 2HDM we used the decay channel $H^\pm H^\pm \rightarrow (W^\pm A^0)(W^\pm A^0) \rightarrow (l^\pm \nu \tau^+ \tau^-) (l^\pm \nu \tau^+ \tau^-)$ together with a pair of forward jets to perform the signal-background
analysis. At the HL-LHC, we can achieve the signal-to-background ratio equal to 1, and the number of signal events is about 2 for a luminosity of 3000 fb$^{-1}$. Nevertheless, at the HE-LHC the significance can rise to the level of $3 - 6$ for $\Delta m = 200 - 250$ GeV.

In summary, if the mass spectrum in 2HDM has the following relations:

- one light (pseudo)scalar, say $A^0$,
- a large mass splitting between two neutral scalars, $\Delta m = (m_{H^0} - m_{A^0})$, and
- the charged Higgs mass is above the $W^\pm A^0$ threshold,

then we can make use of same-sign charged Higgs-boson production to pin down or rule out this scenario in the near future.

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