Charged Higgs Production in Association With $W^{\pm}$ at Large Hadron Colliders

Guo-Li Liu$^{1,3}$, Fei Wang$^{1,3}$, Shuo Yang$^{2,3}$

1 Physics Department, Zhengzhou University, Henan, 450001, China
2 Physics Department, Dalian University, Dalian, 116622, China
3 Kavli Institute for Theoretical Physics China, Academia Sinica, Beijing 100190, China

Many new physics models beyond the standard model, such as the littlest higgs models and the left right twin higgs models, predict the existence of the large charged higgs couplings $H^{-}q\bar{b}$ and $H^{+}b\bar{q}$, where $q = t$ or the new vector-like heavy quark $T$; On the other hand, some new physics models like the littlest higgs also predict the gauge-higgs couplings. Such couplings may have rich collider phenomenology. We focus our attention on these couplings induced by the littlest higgs models and the left right twin higgs models models and consider their contributions to the production cross section for $W^{\pm}H^{\mp}$ production at the large hadron colliders. We find that the cross sections, in the littlest higgs models, on the parton level $gg \rightarrow W^{\pm}H^{\mp}$ and $q\bar{q} \rightarrow W^{\pm}H^{\mp}$ ($q = u, d, s, c, b$) may reach tens of several dozen femtobarns in reasonable parameters space at the collision energy of 14 TeV and that the total cross section can even reach a few hundred femtobarns in certain favored space. While in the left right twin higgs models, the production rates are basically one order lower than these in littlest higgs. Therefore, due to the large cross sections of that in the littlest higgs, it may be possible to probe the charged higgs via this process in a large parameter space.

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I. INTRODUCTION

The primary goal of the Large Hadron Collider (LHC) at CERN is to verify the electroweak symmetry breaking mechanism and to discover or rule out the existence of a higgs boson. Since both the ATLAS and CMS collaborations have discovered a higgs boson-like particle with mass of around 125 GeV at a significance of 5$\sigma$ last year, the goal seems to have been reached.$^{1,2}$ Apart from searches for the higgs boson, there is an ongoing hunting for signals of physics beyond the standard model (SM) at the LHC, and hopefully these experiments will shed some light on physics at the TeV scale.

Due to the incompletion, aesthetical and theoretical problems such as the famous hierarchy problem and triviality problem of the SM higgs boson, various new physics models beyond the SM which try to solve in different ways the previous mentioned problems are proposed. For example, in the Little higgs (LH)$^{3}$ models, the higgs bosons emerges as the pseudo Nambu-Goldstone bosons associate with the spontaneous breaking of a global symmetry. In order to implement the collective symmetry breaking mechanism, new particles such as heavy gauge bosons and top-partners are introduced. Quadratically divergent corrections contributed by such new particles to higgs boson masses cancel out those induced by the top quark and gauge boson loops at one-loop level. Thus no much fine tuning is needed in the LH model with cut off scale $O(10 \text{ TeV})$.

Another example is the left-right twin higgs (LRTH)$^{4}$ models. Again, the higgs bosons in nature are pseudo-Goldstone bosons from spontaneously broken global symmetry. The higgs bosons obtain masses from the gauge and Yukawa interactions which break the global symmetry. As the left-right symmetry was imposed to the twin higgs mechanism, the quadratic terms in the higgs potential respect the global symmetry, and the contributions to the higgs masses cancel out. The logarithmically divergent terms, however, are radiatively generated which are not invariant under global symmetry and contribute masses to the pseudo-Goldstones. The resulting higgs mass is in the field of the electroweak scale with the cutoff at about $5 \sim 10$ TeV.

The LH models and the LRTH models predict multiplet physical higgs bosons, two of which are charged one. Since it is hard to distinguish between the CP-even higgs bosons in such new physics models and the higgs boson in the SM, any observation of a charged higgs will be a crucial signature for new physics beyond the SM. That is why the charged scalar particles have attracted much attention in the previous years by different high energy physics experiments and theories and they will certainly be probed at the LHC.

The search for higgs bosons and new physics particles and the study of their properties are among the prime objectives of the large hadron collider (LHC)$^{5}$. Since the discovery of the charged higgs bosons will be the evidence of new physics beyond the SM, there are increasing interests in theoretical and experimental studies to provide the basis for its accurate exploration. Therefore the LH and LRTH models are very interesting since in these models charged scalars are predicted and they may possess larger tree-level or one-loop top or bottom Yukawa couplings so we may detect the new Yukawa coupling in these models, which may serve as a sensitive probe of the two models.
Much effort is put in the search for charged higgs bosons. From its exclusive decay modes $H^\pm \to \tau\nu$ and $H^\pm \to cs$, the LEP search experiments [6,7] have given a direct limit $M_{H^\pm} > 78.6$ GeV. With different mass range, the search approaches for charged higgs bosons at the hadron collider are distinct. When the charged higgs mass is low, the signal will be $t \to H^+b \to \tau\nu_s b$. The Tevatron search is mainly focused on the low mass range $m_{H^\pm} < m_t$ due to phase space suppression for a heavy charged higgs boson production and any signal of the charged higgs has not been found which means that the mass of the charged higgs is larger than 160 GeV [8]. At the LHC, however, the charged higgs search can be feasible via such as the $gb \to tH^-$ and $gg \to tbH^-$ production up to a large mass range since the LHC collision energy is large [9]. When the charged higgs is heavy $m_{H^\pm} > m_t$, the signal is from the main production process $gb \to tH^-$ and $gg \to tbH^-$ followed by its main decay $H^- \to tb$ [10,11].

Motivated by new technique of "jet substructure" [12–16] developed for highly boosted massive particles, a "hybrid-R reconstruction method", which can use the top tagging and the $m_{H^\pm}$ tagging for other isolated $b$ jets as well as the full reconstructed objects in the final state to suppress the background, is proposed to investigate the full hadronical decay channel of the heavy charged higgs production.

Recently, discussions on neutral or charged higgs production at the LHC have been carried out, see e.g. Refs [17,23]. Both the LH and LRTH models predict neutral or charged ($\phi^0, \phi^\pm$ or $H^\pm$) scalars with large Yukawa couplings to the third generation quarks in addition to a SM-like higgs. They also predict one vector-like heavy top quark $T$ and new gauge bosons ($A_H, Z_H, W_H$). Such new particles can be regarded as a typical feature of these models. Signals of this two models have already been studied in the work environment of linear colliders [18–25], and they may constraint our results. In this paper, to probe the Littlest higgs models and the left right twin higgs models, we shall discuss the production of charged scalar $\phi^\pm$ in association with SM gauge bosons $W^{\pm}$ via those two kinds subprocesses.

This work is organized as follows. In Sec. II we recapitulate the LH models, give the couplings relevant to our calculation and then discuss the numerical results in it. Similarly, in Sec. III the LRTH models are simply described and the numerical results will be given. Finally, we compare the results predicted by the two models and give the conclusion in Sec. IV.

II. THE LH MODEL AND $W^\pm H^\mp$ PRODUCTION AT THE LHC

A. The LH model and the relative couplings

The littlest higgs model [26] is based on the $SU(5)/SO(5)$ nonlinear sigma model. The global symmetry breaks from $SU(5)$ to $SO(5)$, generating 14 Goldstone bosons, and the gauge symmetry from $[SU(2) \times U(1)]^2$ to $SU(2) \times U(1)$, the SM electroweak gauge group. Four of these Goldstone bosons are eaten by the broken gauge generators, resulting in four massive gauge bosons $A_H$, $Z_H$ and $W^\pm_H$. The left 10 states transform under the SM gauge group as a doublet $H$ and a triplet $\Phi$. The doublet VEV further breaks the gauge symmetry $SU(2) \times U(1)$ into $U(1)_Y$, eating three scalar of it and leaving only a CP-even higgs, usually regarded as the SM higgs, which has been discovered at the LHC [1,2].

When the fields rotate to the mass eigenstates, the gauge bosons mix by the mixing angle $s$ and $s'$,

$$s = \frac{g_2}{\sqrt{g_1^2 + g_2^2}}, \quad s' = \frac{g'_2}{\sqrt{g_1^2 + g'_2^2}}$$

In the LH models [20], a new set of heavy vector-like fermions, $\tilde{l}$ and $\tilde{t}^c$, is introduced in order to cancel the top quark quadratic divergence, since they couple to higgs field. Choosing the Yukawa form of the coupling of the SM top quark to the pseudo-Goldstone bosons and the heavy vector pair in the LH models, then diagonalizing the mass terms, one can straightforwardly work out the higgs-quark interactions, as given in Ref. 26, and we repeatedly list here in Table I for convenience.

The couplings, related to our calculation, of the new particles to the SM particles, which include 1) the three-point couplings of the gauge boson to the scalars, including case I: one gauge boson to two scalars and case
II: two gauge bosons and one scalar; 2) charged gauge boson-fermion couplings; 3) the scalar-fermion couplings, which can be found in Ref. [26], are extracted here as:

$$W_L^+ H \Phi^- = -\frac{g}{\sqrt{2}} (\sqrt{2} s_0 - s_+)(p_1 - p_2)_{\mu}$$

$$W_L^+ \Phi^0 \Phi^- = -\frac{g}{\sqrt{2}} (p_1 - p_2)_{\mu}$$

$$W_L^+ \Phi^\mu \Phi^- = \sqrt{2} c_{\Phi}^\mu (p_1 - p_2)_{\mu}$$

$$W_L^+ \Phi^\mu b_L l_L \frac{ig}{\sqrt{2}} (1 - \frac{2}{x_b^2}) \left( \frac{1}{2} x_b^2 \right)^2$$

$$\gamma^\mu V_{tb} P_L$$

$$H_{\Phi}$$

$$\Phi^0 \Phi^-$$

$${\Phi^+}^\mu t b \frac{ig}{\sqrt{2}} (m_t P_L + m_b P_R) \left( \frac{1}{2} - s_+ \right)$$

| particles | $g_V$ | $g_A$ |
|-----------|-------|-------|
| $Z_L \bar{u} u$ | $-\frac{g}{\sqrt{2}} \left( \frac{1}{2} - s_+ \right)$ | $-\frac{g}{\sqrt{2}} \left( \frac{1}{2} - s_+ \right)$ |
| $Z_L \bar{d} d$ | $-\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ | $-\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ |
| $A_H \bar{u} u$ | $\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ | $\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ |
| $A_H \bar{d} d$ | $\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ | $\frac{g}{2c_w} \left( \frac{1}{2} - s_+ \right)$ |
| $Z_H \bar{u} u$ | $-gc/4s$ | $-gc/4s$ |
| $Z_H \bar{d} d$ | $-gc/4s$ | $-gc/4s$ |

TABLE I: The three-point couplings of the gauge boson, the scalars, the fermions in the littlest higgs models. The momenta are taken as $V_L S_1(p_1) S_2(p_2)$ and the particles are in the mass eigenstates with the momenta out-going.

Here $P_L = (1 - \gamma^5)/2$ and $x_L = \lambda_1^2/\left(\lambda_1^2 + \lambda_2^2\right)$, where $\lambda_1$, $\lambda_2$ are the Yukawa coupling of order $O(1)$. The total neutral gauge-fermion couplings can also be extracted as those in Table III [26].

TABLE II: Neutral gauge boson-fermion couplings and $y_u = -2/5$ and $y_c = 3/5$ are required by the anomaly cancelation. The couplings are given in the form $i\gamma^\mu(g_V + g_A\gamma^5)$.

**B. the LH $\phi W$ associated production at the LHC**

At the LHC, the parton level cross sections are calculated at the leading order as

$$\hat{\sigma}(\hat{s}) = \int_{\hat{t}_{\text{min}}}^{\hat{t}_{\text{max}}} \frac{1}{16\pi \hat{s}^2} \sum |M_{\text{ren}}|^2 d\hat{t},$$

with

$$\hat{t}_{\text{max,min}} = \frac{1}{2} \left\{ m_{p_1}^2 + m_{p_2}^2 - \hat{s} \pm \sqrt{\hat{s} - (m_{p_1} + m_{p_2})^2][\hat{s} - (m_{p_1} - m_{p_2})^2] \right\},$$

where $p_1$ and $p_2$ are the first and the second initial particles in the parton level, respectively. For our case, they could be gluon $g$ and quarks $u, d, c, s, b$ etc.

The total hadronic cross section for $pp \rightarrow SS' + X$ can be obtained by folding the subprocess cross section $\hat{\sigma}$ with the parton luminosity

$$\sigma(s) = \int_{\hat{t}_{\text{max}}}^{\hat{t}_{\text{min}}} d\hat{t} \frac{dL}{d\hat{t}} \hat{\sigma}(\hat{s} = st),$$

(4)
where \(\tau_0 = (m_{p_1} + m_{p_2})^2/s\), and \(s\) is the \(pp\) center-of-mass energy squared. \(dL/d\tau\) is the parton luminosity given by

\[
\frac{dL}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} [f^p_{p_1}(x, Q)f^p_{p_2}(1/x, Q) + (p_1 \leftrightarrow p_2)],
\]

(5)

where \(f^p_{p_1}\) and \(f^p_{p_2}\) are the parton \(p_1\) and \(p_2\) distribution functions in a proton, respectively. In our numerical calculation, the CTEQ6L parton distribution function is used \(^{27}\) and take factorization scale \(Q\) and the renormalization scale \(\mu_F\) as \(Q = \mu_F = m_\phi + m_W\). The loop integrals are evaluated by the LoopTools package \(^{23}\).

As for the SM parameters, throughout this paper, we take \(m_t = 173\) GeV \(^{29}\), \(m_W = 80.38\) GeV, \(m_Z = 91.19\) GeV, and \(G_F = 1.16637 \times 10^{-5}\) GeV\(^{-2}\) \(^{30}\), \(\alpha_s(m_Z) = 0.118\) and neglect bottom quark mass as well as other light quark masses.

Now we discuss the main involved LH parameters,

(1) new scalar masses, which include the charged pseudo boson, neutral bosons and the SM-like higgs. The SM-like higgs has been discussed after the CERN experiment data release in e.g, Ref. \(^{31, 32}\), and the discussions show that the LH models may survive when \(f \geq 500\) GeV. We here choose the loose constraints that \(f \geq 500\) GeV and the SM-like higgs mass as the current Experiment value: 125 GeV \(^{1, 2}\). The masses of other scalars \(m_\phi\), despite of the small electromagnetic difference, are the same and the constraints of them are quite loose. We here take \(m_\phi\) as a free parameter varying from 200 GeV to 600 GeV, according to the references such as Ref. \(^{6, 7, 10, 11, 33}\).

(2) The mixing parameter \(s, c\) and \(s', c'\), which are in the range of 0 \(\sim\) 1. We will here take, however, \(s\) free parameter from 0 \(-\) 0.5, and take \(s' = 0.5\) so as the \(c' > 0.62\) according to Ref. \(^{34, 35}\).

(3) As for the scale \(f\), one can have a rough estimate of the natural scale \(^{26}\)

\[
f \leq \frac{4\pi m_H}{\sqrt{0.1a_{\text{max}}}} \approx \frac{8\text{ TeV}}{\sqrt{a_{\text{max}}} \left(\frac{m_H}{200\text{ GeV}}\right)},
\]

(6)

where \(a_{\text{max}}\) denotes the largest coefficient which could be of the order of 10. So for a light \(m_H\), \(f\) may have a lower upper limit.

We here also estimate \(f\) in some particular situation, such as shown in Ref. \(^{35, 36}\), in which the \(U(1)\) sector can be modified by adding an additional \(U(1)_Y\) and only gauging \(U(1)_Y\), in the \(SU(6)/SP(6)\) realization. This may bring \(f\) to survive in the area of less than 1 TeV. In our calculation, we will weaken the constraints a little and take \(500 < f < 2000\) GeV.

(4) About the new gauge boson masses, the charged and the neutral gauge bosons final masses related to our calculation are written as \(^{24}\),

\[
M^2_{W_L} = m^2_w \left[1 - \frac{v^2}{f^2} \left(\frac{1}{6} + \frac{1}{4}(c^2 - s^2)\right) + 4\frac{v'^2}{v^2}\right],
\]

\[
M^2_{Z_L} = m^2_z \left[1 - \frac{v^2}{f^2} \left(\frac{1}{6} + \frac{1}{4}(c^2 - s^2) + \frac{5}{4}(c^2 - s'^2)\right) + 8\frac{v'^2}{v^2}\right],
\]

\[
M^2_{A_H} = m^2_A \left[\frac{f^2}{s^2c^2v^2} + 1 + \frac{c_H c_w^2}{x_H s_w^2}\right],
\]

\[
M^2_{Z_H} = m^2_z \left[\frac{f^2}{s^2c^2v^2} - 1 - \frac{c_H c_w^2}{x_H s_w^2}\right],
\]

(7) (8) (9) (10)

where \(m_z \equiv g v/(2c_w)\) and \(m_w = m_z c_w\) are the SM neutral and charged boson mass, and the \(x_H\) can be found in Ref. \(^{26}\). The masses of the \(Z_H\), however, are still constrained by the LHC experiments. For example, the ATLAS \(^{37, 38}\) and the CMS collaborations \(^{33, 10}\) have detected the heavy vector boson as a di-jet resonance and give the lower limits of the bosons, i.e., \(M_{Z_H} > 1.62\) TeV, which bound the limits of the parameter involved. Since the last term of the \(M_{Z_H}\) in Eq. \(^{10}\) is very small, the first term decides the relation of the parameter \(f\) and \(s\), that is, the parameter \(f\) and \(s\) are restricted by each other when the \(Z_H\) mass range is set. We show in FIG. \(^{11}\) that the contour of the two parameters given the lower limit of the new heavy neutral mass \(M_{Z_H}\). Form FIG. \(^{11}\) we can see that the \(f\) should be large for large \(M_{Z_H}\), but
FIG. 1: In LH, the contour of the parameters $f$ and $s$ for the lower limit of the new heavy gauge boson mass $M_{Z_H} = 1.62$ TeV.

FIG. 2: Feynman diagrams for the charged scalar production associated with the W boson at the LHC via gluon fusion and the quark anti-quark annihilation parton level processes in the LH model. Those obtained by exchanging the two external gluon lines are not displayed here.

if the $s$ becomes small, such as less than 0.15 fb, $f$ may also be small in a narrow parameter space. This, however, influence on our results is not too large since we take a quite a small $s$, for example, $s = 0.1$, in most of calculation unless specifically stated.

(5) If we define $x = 4 f v' / v^2$, where $v'$ is the vacuum expectation value( VEV) of the scalar of the triplet $\phi$, the masses of the neutral boson in the above equations can be rewritten by the parameter $x$ and by this
with the quite large center-of-mass suppression. 

The s-channel contribution of the cross section \( s \), however, is tiny, which is easy to understand respectively, with 

\[
M_{\phi^0}^2 = \frac{2m_{H^0}^2 f^2}{v^2[1 - (4v'f/v^2)^2]} = \frac{2m_{H^0}^2 f^2}{v^2(1 - x^2)}
\] 

The above equation about the mass of \( \phi^0 \) requires a constraint of \( 0 \leq x < 1 \) (i.e., \( 4v'f/v^2 < 1 \) ), which shows the relation between the scale \( f \) and the VEV of the higgs field doublets and the triplet (\( v, v' \)), but this constraint is quite loose, in which the \( v' \) may lie in the range of several GeV, which constraints the parameter \( x \) can not be too large. This is also the constraint coming from \( T \) parameter since \( T \) can be written as \( \alpha T = \rho - 1 = \Delta \rho \). With the constraint of \( v' \) in the order of several GeV, we can here take \( x \) as a free parameter in the range \( 0 < x < 0.2 \), which also indicate clearly that more larger \( x \) is not allowed by current experiments.

(6) In the LH model, the relation among the Fermi coupling constant \( G_F \), the gauge boson W mass \( M_W \) and the fine structure constant \( \alpha \) can be written as \([26, 42]\):

\[
\frac{G_F}{\sqrt{2}} = \frac{\pi \alpha}{2M_W^2 s_W^2} \left[ 1 - c^2(c^2 - s^2) \frac{v^2}{f^2} + 2c^4 \frac{v^2}{f^2} - \frac{5}{4} (c^2 - s^2) \frac{v^2}{f^2} \right] \tag{12}
\]

So we have

\[
\frac{c^2}{s_W^2} = \frac{4\sqrt{2}G_FM_{\phi^0}^2}{\left[ 1 - c^2(c^2 - s^2) \frac{v^2}{f^2} + 2c^4 \frac{v^2}{f^2} - \frac{5}{4} (c^2 - s^2) \frac{v^2}{f^2} \right]} \tag{13}
\]

(7) Finally, the recent data of the 125 GeV higgs also put some constraints on the parameter space \([31]\), but the constraints are quite loose, for example, FIG.1 and FIG.2 in Ref. \([31]\) give the dependence of the ratio \( R = Br(h \rightarrow \gamma\gamma(ZZ))_{LH}/Br(h \rightarrow \gamma\gamma(ZZ))_{SM} \) on the \( f \) and find that they put quite loose constraints to the parameters, so we will not discuss further.

C. numerical results in littlest higgs model

Due to the interactions in Tables I and II, the single charged boson production associated with the W boson processes can proceed through various parton processes at the LHC, as shown in FIG. 2, in which those obtained by exchanging the two external gluon lines are not displayed here. To know the relative values of them, we here, firstly, discuss the contributions from every single parton channel though, actually, we can not distinguish the initial states, i.e, we will firstly discuss the \( gg \) fusion and the \( q\bar{q} \) annihilation processes, respectively, and then sum them all together to see the total contributions.

1. \( gg \) fusion in the LH models

Note that the processes consist of the box diagrams and the W scalar scalar coupling, just shown as FIG. 2 (a) and (b)(c), The s-channel contribution of the cross sections, however, is tiny, which is easy to understand with the quite large center-of-mass suppression.

The production cross sections of the \( \phi^+W^- \) of the \( gg \) fusion are plotted in FIG. 3 for \( E_{cm} = 8, 14 \) TeV, respectively, with \( x = 0, 0.05, 0.1, 0.2 \) and \( f = 500 \) GeV, as functions of the scalar mass \( m_\phi \), assuming the charged and neutral scalar mass degenerate, \( m_{\phi^\pm} = m_{\phi^0} = m_{\phi^*} \). From FIG. 3, we can see the cross section of this process is quite large, about 100 fb in most of the parameter space and, as was expected, the production rate decreases with the increasing scalar mass since the phase space are suppressed by the final masses.

To compare the other parameter dependence, in FIG. 3 (c) (d) we give the cross sections depend on the parameter \( f \) and \( s \), for \( E_{cm} = 8, 14 \) TeV, \( f = 500 \) GeV, and \( m_\phi = 200 \) GeV, which can clearly show the production rate varying as the different parameter. We can see the increasing production rate with the increasing \( s \), but the cross section is decreasing when \( f \) grows up.
FIG. 3: In LH, the cross section \( \sigma \) of the processes \( gg \rightarrow \phi^+ W^- \) as a function of the scalar mass \( m_\phi \) with the center-of-mass energy \( E_{cm} = 8 \text{ TeV} \) (a) and 14 TeV (b) respectively, for \( f = 500 \text{ GeV} \) and \( s = 0.1 \), with different \( x \): \( x = 0 \), 0.05, 0.1, 0.2; the cross section \( \sigma \) of the processes \( gg \rightarrow \phi^+ W^- \) as a function of \( f \) with \( E_{cm} = 8 \text{ TeV} \) (c) and 14 TeV (d) respectively, and \( s = 0.1 \), with different \( x \): \( x = 0 \), 0.05, 0.1, 0.2.

FIG. 4 shows the parameter \( x \) dependence of the cross sections, forgetting the experimental constraints temporally, taking its value from 0 to 0.9 instead. From both FIG. 3 and FIG. 4, we can also see the \( x \) dependence of the process \( gg \rightarrow \phi^+ W^- \) is strong since the \( x = 4f v'/v^2 \) is closely connected to the triplet VEV \( v' \), and the \( v' \) decide the mixing parameter \( s_+ \), the parameter involved in the \( \phi^+ H(H) \). The production cross sections of the processes \( gg \rightarrow W^+ \phi^- + X \) decrease with the increasing parameter \( x \). For example, when the center-of-mass is 8 TeV, for \( x = 0 \), \( m_\phi = 200 \text{ GeV} \), and \( s = 0.1 \), the production rate is about 42 fb; When \( x = 0.2 \), however, the production rate declines to only 27 fb. The larger the \( x \) is, the smaller the cross section is. The situation is the same even \( x \) increasing to 1, though the experiments constrain this parameter far below 1. When the center-of-mass is 14 TeV, the same situation occurs, just the rate will be about an order larger than those of the smaller center-of-mass, i.e., 8 TeV.

As we have discussed, too large \( x \) is excluded by the current data, so a vertical line is added in FIG 4 and in the left of the line is the allowed areas, while the right of it is disallowed. The same situations occur in FIG. 6 and FIG. 8.

The mixing \( s \) affects the process \( gg \rightarrow \phi^+ W^- \) largely, too, however, the trend is different. We can see from FIG. 4 (c) that the possibility of the \( \phi^+ W^- \) associated production increases with increasing \( s \). In FIGS. 3, 4(a)(b), we take \( s = 0.1 \), which is quite small compared to its maximum value, 0.5, according to the discussion of Ref. [34, 35]. So our discussion are not the maximum, the results are general.

Similarly, we can see from FIG. 3(c)(d) that the process \( gg \rightarrow \phi^+ W^- \) is dependent strongly on the parameter \( f \), which is understandable since, the most couplings in the LH models, such as \( \phi^+ H(H) \) and \( \phi^+ W^- S (S = \phi^0, \phi^0, H) \), etc, are tightly connected with the parameter \( f \). The cross sections may be large if the scale \( f \) is
FIG. (2), the t-channel process (d) is free of the center-of-mass suppression and the upraise via space, the largest channel of the processes \(qq\) \(\rightarrow\) \(\phiW\) does not reveal itself. For larger decrease with increasing \(f\), the production rate of this process will go up rapidly. From the couplings, this can also be seen clearly that the annihilations are not so quickly. That can be understood that with the small distribution in the proton, the heavy bosons, i.e., more than 1 TeV, the situation is different immediately. With the increasing \(f\), the production rates decrease largely, which is verified by our calculation though not shown here.

The s-channel processes in FIG. (2) (e), though the parton distribution functions are larger for the \(\bar{u}d\), \(\bar{d}d\), \(c\bar{c}\), \(s\bar{s}\), \(b\bar{b}\) initial states, may be relatively small in view of the center-of-mass suppression effects. At the same time, the t-channel coupling strengths may be large for little \(x\). In FIG. (2)(d), for instance, the strength of \(\phi^+(T)b \sim m_t/v \sim 1\) contributes large. So no wonder the cross sections of the parton level processes like \(u\bar{u}(\bar{d}d, s\bar{s}) \rightarrow \phiW\) are almost unchanged. Actually, if we assume the \(\phi^+\) mass are in the order of the heavy bosons, i.e., more than 1 TeV, the situation is different immediately. With the increasing \(m_\phi\), the production rates decrease largely, which is verified by our calculation though not shown here.

The s-channel processes in FIG. (2) (e), though the parton distribution functions are larger for the \(u\bar{u}\) and \(d\bar{d}\) initial states, may be relatively small in view of the center-of-mass suppression effects. At the same time, the t-channel coupling strengths may be large for little \(x\). In FIG. (2)(d), for instance, the strength of \(\phi^+(T)b \sim m_t/v \sim 1\) contributes large. So no wonder the cross sections of the parton level processes like \(u\bar{u}(\bar{d}d, s\bar{s}) \rightarrow \phiW\) are almost unchanged. Actually, if we assume the \(\phi^+\) mass are in the order of the heavy bosons, i.e., more than 1 TeV, the situation is different immediately. With the increasing \(m_\phi\), the production rates decrease largely, which is verified by our calculation though not shown here.

With the increasing \(f\), the cross sections decrease with increasing charged scalar mass \(m_\phi\), the level of decline, however, is different. For \(b\bar{b}\) realization, we can see it declines rapidly, while the \(u\bar{u}\), \(d\bar{d}\), \(s\bar{s}\), \(c\bar{c}\) annihilations are not so quickly. That can be understood that with the small distribution in the proton, the \(b\bar{b}\) collisions mainly contribute via the t-channel, while the others are from s-channels mediated by the bosons \(A_H\), \(Z_L\), \(Z_H\) which appear in the propagator, with large masses about 1 TeV, which weakens the effect of the increasing scalar mass. When \(m_\phi\) is not too large compared to the heavy boson mass, the cross sections from s-channel \(qq\) annihilations are almost unchanged. Actually, if we assume the \(\phi^+\) mass are in the order of the heavy bosons, i.e., more than 1 TeV, the situation is different immediately. With the increasing \(m_\phi\), the production rates decrease largely, which is verified by our calculation though not shown here.

The s-channel processes in FIG. (2) (e), though the parton distribution functions are larger for the \(u\bar{u}\) and \(d\bar{d}\) initial states, may be relatively small in view of the center-of-mass suppression effects. At the same time, the t-channel coupling strengths may be large for little \(x\). In FIG. (2)(d), for instance, the strength of \(\phi^+(T)b \sim m_t/v \sim 1\) contributes large. So no wonder the cross sections of the parton level processes like \(u\bar{u}(\bar{d}d, s\bar{s}) \rightarrow \phiW\) are almost unchanged. Actually, if we assume the \(\phi^+\) mass are in the order of the heavy bosons, i.e., more than 1 TeV, the situation is different immediately. With the increasing \(m_\phi\), the production rates decrease largely, which is verified by our calculation though not shown here.

Note that in FIG. (5), the processes depend largely on the parameter \(f\), and if the parameter \(f\) decreases, the production rate of this process will go up rapidly. From the couplings, this can also be seen clearly that the \(\phi(T)b \sim 1/f\), while in the s-channel, the couplings \(V\phiW (V = A_H, Z_L, Z_H) \sim v', v' = xv^2/(4f)\), so they decrease with increasing \(f\). The exception, however, occurs in FIG. (5)(c)(d) and therefore FIG. (6).

From FIG. (3), we can also see that, when \(x\) is small, such as 0.1 which we have chosen, in the most parameter space, the largest channel of the processes \(qq \rightarrow \phiW\) is the \(b\bar{b} \rightarrow \phiW\), which is easy to understand since, in FIG. (2), the t-channel process (d) is free of the center-of-mass suppression and the upraise via \(x\) i.e., the \(v'\) does not reveal itself. For larger \(x\), however, the situation changes. We can see from FIG. (6) that, except via \(bb\) annihilation, the quark anti-quark processes are increasing with the increasing \(x\).
FIG. 5: In LH, the cross section $\sigma$ of the processes $q \bar{q} \rightarrow \phi^+ W^-$ as a function of the scalar mass $m_\phi$ with $E_{cm} = 8$ TeV (a) and 14 TeV (b) for $f = 500$ GeV, $x = 0.1$ and $s = 0.1$; The $q \bar{q} \rightarrow \phi^+ W^-$ cross section $\sigma$ as a function of $f$ with $E_{cm} = 8$ TeV (c) and 14 TeV (d) respectively, and $s = 0.1$, $x = 0.1$. Here $q = u, d, c, s, b$ quarks.

FIG. 6 is the cross sections of the quark anti-quark annihilations on the parameter $x$, taking $x$ from 0 to 0.9, too. In FIG. (6) we can see that with the increasing parameter $x = 4f v'/v^2$, the trends of the cross sections are different with those in FIG. 4. When $x > 0.2$ the cross sections from the $u\bar{u}$ collision begin overwhelming that from $b\bar{b}$ at 14 TeV, which is opposite to the above discussion. The reason is given in the following, the same as the comparison of $\phi W$ production via $gg$ fusion and $q \bar{q}$ annihilation.

Now, compared the FIG. (4) (c) with FIGs. (6), (8), we can find that the $\phi W$ associated production from $gg$ fusion and $b\bar{b}$ annihilation decreases with increasing $x$, while those from other quark anti-quark annihilation ($u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$) is opposite, which is understandable from their different coupling forms. Since the $VW_L \phi^+$ ($V = A_L, Z_L, Z_H$) is proportional to $v'$, while $\phi(T)b$ is in proportion to $\frac{v}{v'} - 2s_+$, here $s_+ = 2v'/v$. In the scalar-fermion couplings, actually, there is a competition between the two terms $\frac{v}{v'}$ and $2s_+$. When $f = 500$ GeV, $v/f \sim 0.5$, the $2s_+$, however, less than 0.5 all the time if we satisfy the requirement $v' < 30$, i.e., $x < 0.2$, so with the increasing $v'$, the couplings $\phi(T)b$ is decreasing.

3. Total contribution of the $gg$ and quark anti-quark annihilation

In FIGs. (7), (8) we sum the contributions from all the parton level processes. We can see from the figures that the cross sections can arrive at tens of fb even when $E_{cm} = 8$ TeV, and when the center-of-mass rises to 14 TeV, the production rates will become more large, larger than $10^0$ fb in quite a large parameter space. So in the discussion of reducing the backgrounds, we will concentrate to the 14 TeV center of mass.
With the increasing $x$, the s-channel contributions of the $q\bar{q}$ annihilation contribute more and more large, so then the $gg$ fusion and $b\bar{b}$ collision, the t-channel dominant, are not the largest any more, but instead, the $uu$ and $dd$ will control the situation, which can be seen clearly in FIG. 7.

From FIG. 7 we can see that the production rates of the $\phi^+W^-$ decrease when $m_\phi$ or $f$ goes up. Note that in FIG. 7 (c)(d), with the increasing $f$, in the tail of the curve for $pp \rightarrow \phi^+W^-$, $x = 0.7$, the cross sections increase when $f$ changes from 1500 GeV to 1700 GeV, which is understandable, when $x$ is large, the contributions from the s-channel surpass that from the t-channel, i.e, the $gg$ and $b\bar{b}$ realization.

III. THE LRTH MODEL AND $\phi W$ PRODUCTION AT THE LHC

A. The LRTH model and the relevant couplings

To solve the little hierarchy problem \[43\], the left right twin higgs models was proposed \[44, 45\]. In this models, The higgses emerge again as pseudo-Goldstone bosons and the leading order of the the higgses masses is quadratically divergent. One introduces an additional discrete symmetry so that the leading quadratically divergent terms respect the global symmetry. With the cancellation of the quadratically divergent, then the higgs masses passes logarithmically divergent contributions.

In such models, the global symmetry breaks from $U(4) \times U(4)$ to $U(3) \times U(3)$, and gauge symmetry from $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ to $SU(2)_L \times U(1)_Y$. Fourteen Goldstone bosons are generated, three of which are eaten by the massive gauge bosons $Z_H$ and $W^\pm_H$, while the rest of the Goldstone bosons contain the SM $SU(2)_L$ higgs doublet and extra higgses.

To cancel the leading quadratically divergence of the SM gauge bosons and the top quark contributions to the higgs masses in the loop level, the new heavy gauge bosons and a vector top singlet pair are introduced. Thus the hierarchy problem is solved. The new particles in the LRTH, both the gauge bosons and the vector top singlet, have rich phenomenology at the LHC and people are interested in them.

The two higgs fields, $H$ and $\hat{H}$ acquire two non-zero VEVs which break the $U(4) \times U(4)$ to $U(3) \times U(3)$ and yields 14 Goldstone bosons, six of which are eaten by the massive gauge bosons. Finally, there are one neutral pseudoscalar $\phi^0$, a pair of charged scalar $\phi^\pm$, the SM physical higgs $h$, which representation of $(\phi^+, \phi^0)$ is $(1,2,1)$ in the gauge group $SU(3)_L \times SU(3)_R \times U(1)_{B-L}$. A $SU(2)_L$ doublet $\tilde{h} = (\tilde{h}^+_1, \tilde{h}^0_2)$ are also left in the higgs spectrum.

The quantum numbers of gauge bosons of $W^\pm$ and $W^\pm_H$ are $(3,1,0)$ and $(1,3,0)$. After the symmetry breaking, the six physically massive gauge bosons are four charged and two neutral ones: $W^\pm, W^\pm_H, Z$ and $Z_H$. $W$ and $Z$ are the usual massive gauge bosons in the SM and $W_H$ and $Z_H$ are three additional new massive gauge bosons with masses of TeV.

The Lagrangian concerning of the new particles can be written as

$$\mathcal{L} = \mathcal{L}_H + \mathcal{L}_G + \mathcal{L}_f + \mathcal{L}_Y + \mathcal{L}_{\text{one-loop}} + \mathcal{L}_\mu. \quad (14)$$

![FIG. 6](image_url)  

**FIG. 6**: In LH, the cross section $\sigma$ of the processes $q\bar{q} \rightarrow \phi^+W^-$, with $m_\phi = 200$ GeV, $f = 500$ GeV as a function of $x$ for $E_{cm} = 8$ TeV (a) and 14 TeV (b) ($s = 0.1$).
The various terms in Eq. (14) are covariant kinetic terms for higgses, gauge bosons and fermions, Yukawa interactions, one-loop Coleman-Weinberg (CW) potential for higgses and soft symmetry breaking $\mu$ terms. The explicit expression can be found in Ref. [45] and we here not list repeatedly.

Based on the Lagrangian given in Ref. [45], we have, the couplings with fermions involved, which are concerned of our calculation [43].

The three-point couplings of the charged gauge boson-fermion-fermion and those of the scalar-fermion-fermion in the LRTH models. The chirality projection operators are $P_{R,L} = (1 \pm \gamma_5)/2$.

As for the coupling between the boson and the scalars, we find that they all vanish, if we parameterize the scalars in the Goldstone bosons fields as $[45].$

\[
N \to \frac{\sqrt{2} i}{F(\cos x + 2 \sin \frac{x}{2})} \phi^0, \quad \hat{N} \to \frac{\sqrt{2} i \cos x}{3F} \phi^0, \\
h_1 \to 0, \quad h_2 \to \frac{v + h_2}{\sqrt{2} F(\cos x + 2 \sin \frac{x}{2})} \phi^0, \\
C \to -\frac{x}{F \sin \frac{x}{2}} \phi^+, \quad \hat{C} \to \frac{F \cos x}{x} \phi^+.
\]
FIG. 8: The total cross section $\sigma$ of the processes $pp \to \phi^+ W^-$ as a function of $x$ with the scalar mass $m_\phi = 200$, 400, 600 GeV, $s = 0.1$ and $E_{cm} = 8$ TeV (a) and $E_{cm} = 14$ TeV (b).

where the $N, \hat{N}, h_1, h_2, C, \hat{C}$ are in the Goldstone bosons fields,

$$H = \frac{\sin \sqrt{X}}{\sqrt{X}} e^{i \frac{\sqrt{X}}{2}} \begin{pmatrix} h_1 \\ h_2 \\ N - i f \sqrt{X} \cot \sqrt{X} \end{pmatrix}, \quad \hat{H} = \frac{\sin \sqrt{\hat{X}}}{\sqrt{\hat{X}}} e^{i \frac{\sqrt{\hat{X}}}{2}} \begin{pmatrix} \hat{h}_1 \\ \hat{h}_2 \\ \hat{N} - i f \sqrt{\hat{X}} \cot \sqrt{\hat{X}} \end{pmatrix}. \quad (16)$$

By this parameterization, the requirement of vanishing gauge-higgs mixing terms can be satisfied, i.e, in this redefinition of the higgs fields, the couplings $WZ\phi^+, W\gamma\phi^+, WZ_H\phi^+, W_H\phi^+, W\phi^0\phi^+, W\phi^0\phi^+$ are zero, which has been verified by our written calculation. This is quite different with that in the littlest higgs models.

B. LRTH $\phi W$ production at the LHC and the numerical results

Due to the missing of the gauge-higgs mixing terms, the associated production of the charged scalar $\phi^+$ and the charged gauge boson $W$ is different with that in the little higgs models. In FIG. (2), the figures (a) and (e) will not occur in the LRTH models since they contain the gauge-higgs mixing couplings, while the others are kept and they are the realization of the $\phi W$ production in the LRTH models.

When discussing the numerical results of the processes, just as the discussions in LH models, we also, firstly, investigate the contributions from every single parton channel, i.e, the $gg$ fusion and the $q\bar{q}$ annihilation processes, respectively, and then sum them for the total contributions.

1. $gg$ fusion in the LRTH models

Different with that of the LH models, the $\phi W$ associated production are carried out only by the box diagrams from $gg$ fusion and $t$-channel contribution via the quark anti-quark annihilation, just shown as FIG. (2) (b)(c) and (d), and the $s$-channels in FIG. (2) (a) (e) are missing.

The production cross sections of the $\phi^+ W^-$ of the $gg$ fusion are plotted in FIG. (9) with $M = 100$, 300, 500 GeV for $E_{cm} = 8, 14$ TeV and for $f = 500$ GeV, as functions of the scalar mass $m_\phi$, assuming the charged and neutral scalar mass degenerate, $m_\phi^+ = m_\phi^0 = m_\phi^p$. From FIG. (9), we can see the cross section of this process is less than 50 fb in most of the parameter space, even for a larger center-of-mass energy, i.e, at 14 TeV with $M = 500$ GeV. We can also see that, as expected, the production rate decreases with the increasing scalar mass since the phase space are suppressed by the mass.

FIG. (9) show the different dependence of the cross sections on the parameter $M$, with $M = 100$, 300, 500 GeV. The results change with the varying values of $M$ and when $M$ is large, such as
FIG. 9: In LRTH, the cross section $\sigma$ of the processes $gg \to \phi^+W^-$ as a function of the scalar mass $m_\phi$ or $f$ with $E_{cm} = 8$ TeV and $E_{cm} = 14$ TeV for $M = 100, 300, 500$ GeV.

When $M$ is very small, such as $\lesssim 1$ GeV, the collider phenomenology of the $\phi^+W^-$ will very small, which can be seen clearly via the two group couplings that realize the $\phi^+W^-$ associated production. The $\phi^+tb$ and $W^+\bar{t}b$ couplings, for example, are $(S_Rm_bP_L - y_SLf_P_R)/f$ and $\gamma_\mu C_LP_L/(\sqrt{2}s_w)$, respectively, with $S_L, S_R \sim M/M_T$ and $C_L = \sqrt{1 - S_L^2}$. So when $M$ is small, $S_L, S_R$ will become small too. When $M = 0$, $S_L, S_R$ also change into 0. So if $M$ is too small, the signal will be very small. In the limit case, when $M = 0$, the light top will not mix with the heavy top, so the couplings $\phi^+tb$ disappear, and the contribution are only from the heavy top coupling to the scalar. But the light charged scalar is opposite, which, mainly coupled to the light top, the heavy top couplings $W^+\bar{T}b$, proportional to $S_L \sim M$, disappear. So the cross section will drop down to zero when $M$ is in its limit $M = 0$.

We can also see from FIG. 9 that the process $gg \to \phi^+W^-$ is dependent strongly on the parameter $f$, which is understandable since, the most couplings in the LRTH models, such as $\phi^+tb, \phi^+Tb$, etc, are tightly connected with the parameter $f$. The cross sections may be larger unless $f$ is not too high. The rates of the $\phi^+W^-$ production for $\sqrt{s} = 14$ TeV and $m_\phi = 200$ GeV, for example, are 52 fb and 7 fb, for $f = 500$ GeV and $f = 1000$ GeV, respectively.

2. $b\bar{b}$ annihilation in the LRTH models

Unlike that in the LH models, in LRTH, the $\phi W$ production via quark anti-quark annihilation are realized only by the t-channel parton level $b\bar{b} \to \phi W$, which is because we have expected the higgs-gauge coupling vanishing, so the s-channel processes are missing, and only the t-channel processes proceeding by the $t-b$ and $T-b$ mixings survive.

Due to the small parton distribution functions, the $b\bar{b}$ realization of the $\phi W$ production, which is tree-level, is not quite large, can arrive at about 20 fb, a little smaller than that of the $gg$ fusion in the loop level realization.

At the same time, we can see that the process $b\bar{b} \to \phi W$ depends largely on the parameter $M$ and $f$, and if $f$
FIG. 10: In LRTH, the cross section $\sigma$ of the processes $q\bar{q} \rightarrow \phi^+W^-$ as a function of $m_\phi$ or $f$ for $M = 150, 250, 500$ GeV with the scalar mass $m_\phi = 200$ GeV and $E_{cm} = 8$ TeV and $E_{cm} = 14$ TeV.

The production rate of this process will decreases, but for parameter $M$, the cross sections will increase with the increasing parameter $M$, which can be also seen in FIG. 10.

3. Total Contribution of the gg and quark anti-quark Annihilation

In LRTH models, we sum all the contribution, from $gg$ fusion and $b\bar{b}$ annihilation for the $\phi^+W^-$ associated production in FIG. 11, and from which, we can see that the cross section can arrive at tens of fb, dependent on the parameter $f$, $M$ and the scalar mass in a certain center-of-mass $E_{cm}$. But in quite a large parameter space, the cross sections are less than 10 fb. Normally, at the LHC, this will not interest us, so we will discuss little, also in the following section.

IV. BACKGROUNDS AND DETECTIONS

From the data above, we can see that, at $E_{cm} = 8$ TeV, no matter LH or LRTH models, the cross section of the charged higgs associated with a $W$ boson production is quite small, even with a little scalar mass, such as 200 GeV, supposing the luminosity to be $10^{-1}\text{ fb}^{-1}$. It is easier, however, for the charged higgs boson to be observed at $E_{cm} = 14$ TeV. Therefore from now on we focus on investigating the charged higgs associated with a $W$ boson in the following processes at the 14 TeV. The following signatures can be considered [47]:

$$pp \rightarrow W^-H^+ \rightarrow W^-t\bar{b} \rightarrow l^-\nu b\bar{b}jj,\quad pp \rightarrow W^+H^- \rightarrow W^+t\bar{b} \rightarrow l^+\nu b\bar{b}jj$$

(17)

at $E_{cm} = 14$ TeV with $200 \leq m_\phi \leq 600$ GeV.

For the processes above with final state $l + E_T + b\bar{b}jj$, the dominant SM backgrounds are $t\bar{t}, t\bar{t}W, t\bar{t}Z, WZjj, WWjj$ and $Wjjjj$, which are discussed in Ref. [47]. In the signature of the $H^\pm W^\mp$ production processes, the charged higgs decays to four jets and top quark decay to three of them. Thus to make clear of the signal, one can
FIG. 11: In LRTH, the total cross section $\sigma$ of the processes $\phi^+W^-$ associated production from $gg$ fusion and $b\bar{b}$ collision as a function of the scalar mass $m_\phi$ or $f$ with $E_{cm} = 8$ TeV and $E_{cm} = 14$ TeV for $f = 500$, 1000 GeV for different $M$ ($M = 100$, 300, 500 GeV).

make the requirements like these: 1) the invariant mass of final four jets is around the charged higgs mass, and 2) three jets of the four reconstruct into top quark mass. To suppress the $t\bar{t}$ final state, the dominant channels of the backgrounds, one can construct the second top quark. The final results given in Ref. [47] show that after all cuts, the signal process is only 1 fb left when $m_{H^\pm} = 500$ GeV, and the backgrounds are becoming negligibly small. Ref. [47] also points out in Table I and II, with the increasing charged scalar mass, the backgrounds become smaller and easier to be suppressed, so it seems that the larger the charged scalar mass is, the easier to detect the $WH$ production at the LHC, though the cross section of the signals will also be smaller.

From Ref. [47] Table II, we can see that if the scalar mass is 400 GeV, the $S/\sqrt{B}$ can reach 3.42, and with the increasing $m_S$ (scalar mass), the $S/\sqrt{B}$ gets larger, so we will focus the scalar mass at 400 GeV and larger. From Table I of Ref. [47], we can see if $m_S = 400$ GeV, when the cross section arrive at 49.7 fb, the $S/\sqrt{B}$ will be larger than 3.

Table IV give the optimum value of the $\phi^+W^-$ production in the LH and the LRTH models at the 14 TeV when $m_\phi = 400$ GeV. The parameters are set as: 1) In the LH models, $s = 0.1$, $s' = 0.5$, $f = 500$, 1000 GeV. 2) In the LRTH models, the involved parameters are $Y = 1$, $f = 500$, 1000 GeV.

|     | LH    | x=0   | x=0.05 | x=0.1  | x=0.15 | x=0.2  |
|-----|-------|-------|--------|--------|--------|--------|
| $f=500$ | 87.22 | 79.23 | 72.33  | 66.44  | 61.59  |
| $f=1000$ | 27.84 | 25.12 | 22.55  | 20.11  | 17.83  |
|     | LRTH  | M=0   | M=100  | M=300  | M=500  | M=700  |
| $f=500$ | 0     | 1.9   | 12.5   | 22.4   | 29     |
| $f=1000$ | 0     | 0.10  | 0.86   | 2.07   | 3.36   |

TABLE IV: For $m_\phi = 400$ GeV, the cross section of the signal process at $E_{cm} = 14$ TeV for $f$ and $M$ in unit of GeV, cross sections in unit of fb.
From Table IV, we can see that in the LH, when $m_S = 400 \text{GeV}$, for the small scale $f$, the cross sections are larger than 49.7 fb, the value for the $3\sigma$ confidence level. While for the LRTH, it is dangerous to reach the detectable level in the most parameter space. In LH models, when $f$ is large, the production rates will be suppressed and smaller than 49.7 fb, which will be hardly to probe. The cross sections, however, are also sensitive to the parameters $s$ and $s'$, this would give quite larger results if we fine tune the parameters. When $s = s' = 0.1$, for example, the production can even arrive at 1000 fb. However, this fine-tuning is not what we want, since it only in a little parameter space and we should consider the confinements such as Ref. [34, 35].

In LH models, however, we can also consider the larger scalar mass, such as 600 GeV, according to Table I and Table II in Ref. [47], the cross sections before cuts is about 14 fb, and the $S/\sqrt{B}$ is 8.77 with the integral luminosity 300 fb$^{-1}$. We calculate the rate of the $\phi W$ production at $m_\phi = 600 \text{ GeV}$ for $f = 1000 \text{ GeV}$ and $s = 0.1$, we just find that the cross section can arrive at about 9 fb, which is close to 14 fb. So we can image that the signal and backgrounds $S/\sqrt{B}$ should be large, at least larger than 3 for such a large cross section for $m_\phi = 600 \text{ GeV}$. So we may conclude that for a larger scalar mass, the associated production could be more easily to be detected.

As for the other production modes of the charged higgs in LH and LRTH models, the pair production should be the most interesting one since the order may be large. For the two models, the large SM backgrounds do not take too much luck to the detection, just stated as Ref. [24], it may only be possible for the charged higgs to be produced in quite a narrow space. The pair productions of the neutral higgs are also discussed [24] and be also possible in a narrow parameter space. Other production modes of the higgs in LH and LRTH models such as $ZH$, $tH$ and $ZHH$ are also studied.

If one wants to detect all these procedures list above, the common requirements are that both the $f$ and the higgs masses are not too large, which are agreed in principle with $W$ and the charged higgs associated production, which has been discussed in this work. Larger $f$, e.g., $f > 1000 \text{ GeV}$, however, is preferred by current constraints, so it may be an another interesting issue to consider a larger boson mass to carry out the detection of this signal. As we have discussed, it may also be possible to be probed in a small parameter spaces. Though $f$ is relatively large ($f > 800 \text{ GeV}$), we in this work show with a smaller $f$ ($f$ from 500 to 2000 GeV), too, to see the impact of this parameter on the associated production.

V. CONCLUSION AND SUMMARY

We calculate the charged scalar production associated with a gauge boson $W$ in the LH models and the LRTH realizations. Comparing the two kinds of models, we can see that, at the LHC, the $\phi W$ production in the LH models are larger than that in the LRTH models, and the LH models should be more more possible to be detected at the LHC via the $\phi^+W^-$ production. From the discussion above, we can also conclude that, in LH models, for a small $f$, in most parameter space of the LH model, the production rates can arrive at the detectable level. But when $f$ is large, the suppression effect becomes strong, so it may difficult for LHC to detect the signal. With a larger scalar mass, however, the signal will be a little easier to detect.

Acknowledgments

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\[ \sigma(q\bar{q} \rightarrow \phi^+ W^-)(fb) \]

\[ \sqrt{S} = 14\text{TeV} \]

- \( \mu\bar{\mu} \)
- \( d\bar{d} \)
- \( s\bar{s} \)
- \( b\bar{b} \)
- \( c\bar{c} \)