Long-lived charged Higgs at LHC as a probe of scalar Dark Matter

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ABSTRACT

We study inert charged Higgs boson $H^\pm$ production and decays at LHC experiments in the context of constrained scalar dark matter model (CSDMM). In the CSDMM the inert doublet and singlet scalar’s mass spectrum is predicted from the GUT scale initial conditions via RGE evolution. We compute the cross sections of processes $pp \rightarrow H^+H^-, H^\pm S^0_i$ at the LHC and show that for light $H^\pm$ the first one is dominated by top quark mediated 1-loop diagram with Higgs boson in s-channel. In a significant fraction of the parameter space $H^\pm$ are long-lived because their decays to predominantly singlet scalar dark matter (DM) and next-to-lightest (NL) scalar, $H^\pm \rightarrow S_{DM,NL}f\bar{f}'$, are suppressed by the small singlet-doublet mixing angle and by the moderate mass difference $\Delta M = M_{H^+} - M_{DM}$. The experimentally measurable displaced vertex in $H^\pm$ decays to leptons and/or jets and missing energy allows one to discover the $H^+H^-$ signal over the huge $W^+W^-$ background. We propose benchmark points for studies of this scenario at the LHC. If, however, $H^\pm$ are short-lived, the subsequent decays $S_{NL} \rightarrow S_{DM}f\bar{f}$ necessarily produce additional displaced vertices that allow to reconstruct the full $H^\pm$ decay chain.

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1 Introduction

The existence of cold dark matter (DM) of the Universe is firmly established by cosmological observations [1]. Because the SM does not contain a cold DM candidate, its existence is a clear signal of new physics beyond the SM. However, the origin, nature and properties of the DM have so far remained completely unknown. The Tevatron and the LHC experiments aim to reveal the origin of electroweak symmetry breaking (EWSB) and to discover directly the DM particle. In the standard model (SM) there is just one fundamental scalar doublet $H_1$ and the EWSB occurs spontaneously due to its explicitly negative mass parameter $\mu^2_1$ in the scalar potential. In the SM the Higgs boson, the only scalar particle to be discovered, cannot be the DM candidate.

However, it is possible that the two issues are related in models with an extended scalar sector. The SM Higgs boson mass term $\mu^2_1 H_1^\dagger H_1$, being superrenormalizable, may open a portal into a hypothetical hidden sector [2]. Combining this idea with a scenario that cold DM of the Universe consists of a $Z_2$-odd SM singlet $S$ [3] and/or doublet $H_2$ [4] scalars implies that the SM Higgs boson opens a portal into DM. It is also possible that the new scalar DM sector actually triggers the EWSB by driving $\mu^2_1$ negative by some dynamical mechanism. In order to formulate this interesting but purely phenomenological scenario in the form of DM theory one needs theoretical guidance from the underlying principles of new physics.

It was shown in [5, 6] that the high energy theory for the low scale scalar DM models can be non-SUSY $SO(10)$ Grand Unified Theory (GUT) [7]. Indeed, the discrete $Z_2$ symmetry, which makes DM stable, could be an unbroken remnant of some underlying $U(1)$ gauge subgroup [8]. This argument is completely general and does not require the existence of additional symmetries such as supersymmetry[1]. If the GUT gauge group is $SO(10)$, the argument of [8] implies [5, 6] that non-supersymmetric DM should most naturally be embedded into a scalar representation 16 because this is the only small representation that is odd under the generated discrete gauge symmetry – the matter-parity

$$P_M = (-1)^{3(B-L)}. \quad (1)$$

In this framework the generation of matter-parity $P_M$ is directly related to the breaking of gauged $B-L$, implying that the dark sector actually consists of $P_M$-odd scalar relatives of the SM fermions[2]. In this scenario the origin and stability of DM, the non-vanishing neutrino masses via the seesaw mechanism [11] and the baryon asymmetry of the Universe via leptogenesis [12] all originate from the same source – the breaking of $SO(10)$ gauge symmetry. In addition, the EWSB may occur dynamically due to the Higgs boson interactions with the dark sector scalars [6,13,14].

The inert charged Higgs boson production and decays at the LHC experiments have been

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1 In the context of minimal supersymmetric standard model (MSSM) R-parity [9] is imposed by hand to prevent phenomenological disasters such as a rapid proton decay. In MSSM the R-parity is equivalent to the matter-parity [10] that is imposed at superfield level.

2 In the context of supersymmetry the scalar particles with the same quantum numbers are called squarks and sleptons. This scenario suggests generally that what we call “matter” must consist of $P_M$-odd particles.
previously studied in three papers \cite{15,16,17}. Working in the context of inert doublet model \cite{4}, those papers conclude that it is impossible to discover the production processes \( pp \rightarrow H^+H^-, H^\pm S \) followed by the decays \( H^\pm \rightarrow S_{\text{DM}}\ell^\pm \nu \), where \( S_{\text{DM}} \) is the DM scalar, over the huge \( W^+W^- \) background. However, as explained above, the inert doublet model represents just one particular corner of parameter space of the general \( P_M \)-odd scalar DM scenario in which the DM is (predominantly) doublet.

From the fundamental physics point of view a better motivated scalar particle spectrum is obtained from the GUT scale initial parameters by their renormalization group (RG) evolution down to the low scale \cite{6}. This procedure is analogous to obtaining the low scale sparticle spectrum in the constrained MSSM. In our scenario the constrained scalar DM model (CSDMM) predicts that in the majority of parameter space the DM scalar is predominantly singlet and that \( H^\pm \) and \( S_{\text{DM}} \) are relatively close in mass. Therefore the decays \( H^\pm \rightarrow S_{\text{DM,NL}}ff' \), where the next-to-lightest neutral scalar \( S_{\text{NL}} \) is almost degenerate with \( S_{\text{DM}} \) and \( ff' \) are the SM quarks and leptons, may be suppressed by two factors: (i) by the small singlet-doublet mixing angle; (ii) by the small mass difference \( \Delta M = M_{H^+} - M_{\text{DM}} \). Thus the inert \( H^\pm \) may be long-lived, travel a macroscopic distance inside the tracker of a LHC experiment, and decay far from the interaction point into charged lepton or jets and missing \( E_T \). The experimental signature of the displaced vertices in \( H^\pm \) decays are theoretically free from the SM background and enable to discover \( H^\pm \) at the LHC.

In this work we study charged Higgs boson phenomenology of the constrained scalar DM model. Because \( H^+ \) does not have Yukawa couplings, we traditionally call it inert charged Higgs boson even though it does have gauge couplings. There are several differences between the phenomenology of the charged Higgs boson of the two Higgs doublet models (2HDM) and the phenomenology of the inert charged Higgs boson. First of all, the inert charged Higgs boson is coupled only to bosons (scalars or gauge vectors), and its interactions are determined by the matter-parity conservation. Moreover, it is the charged component of only the \( P_M \)-odd doublet and does not mix with the charged component of the SM Higgs doublet. As a consequence, there are no free parameters such as \( \tan \beta \). These features will affect the inert charged Higgs production and decays to be studied in this paper.

We first review the basics of the constrained scalar DM model \cite{6}. After that we study the production and the decays of the inert charged Higgs boson at the LHC experiments. First we show that for light charged Higgs scalar the 1-loop top quark mediated production process with the Higgs boson in the \( s \)-channel dominates over the tree level processes considered in papers \cite{15,16,17}. This is an important new result of our paper which agrees with the similar result obtained for the production of a pair of neutral inert scalars \cite{18}. After that we show that the constrained scalar DM model may imply a long lifetime of \( H^+ \) which, in an appreciable fraction of the parameter space, may imply observable displaced vertices at the LHC. This is a background-free experimental signature of the inert charged Higgs boson. Further we argue that if \( H^\pm \) is short-lived, the decay chain \( H^\pm \rightarrow S_{\text{NL}}ff' \) followed by \( S_{\text{NL}} \rightarrow S_{\text{DM}}ff \) will necessarily produce a displaced vertex in the latter decay that allows to reduce the background. Throughout of this paper we consider two scenarios of the constrained scalar DM models, one without requiring radiative EWSB and another with the requirement of radiative EWSB. The
2 The constrained scalar Dark Matter model (CSDMM)

The CSDMM is obtained from the minimal non-supersymmetric matter-parity-odd scalar $SO(10)$ model by decoupling of all new $SU(2)_L \times U(1)_Y$ scalar multiplets that do not contain the DM candidates. This implies that the scalar sector of CSDMM consists of the Higgs boson $H_1$, the inert doublet $H_2$ and the singlet $S$. The minimal $P_M$-odd scalar $SO(10)$ GUT scenario$^3$ contains the SM Higgs boson in a scalar representation 10 and the DM candidates in a scalar representation 16. Thus below the $M_G$ and above the EWSB scale the model is described by the $H_1 \rightarrow H_1$, $S \rightarrow -S$, $H_2 \rightarrow -H_2$ invariant scalar potential

$$V = \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2$$

$$+ \mu_3^2 S^\dagger S + \frac{\mu_5^2}{2} [S^2 + (S^\dagger)^2] + \lambda_3 (S^\dagger S)^2$$

$$+ \frac{\lambda_5}{2} \left[ S^4 + (S^\dagger)^4 \right] + \frac{\lambda_6}{2} (S^\dagger S) [S^2 + (S^\dagger)^2]$$

$$+ \lambda_{11} (S^\dagger S) (H_1^\dagger H_1) + \lambda_{12} (S^\dagger S) (H_2^\dagger H_2)$$

$$+ \frac{\lambda_{13}}{2} \left[ (H_1^\dagger H_1)^2 + (H_2^\dagger H_2)^2 \right]$$

$$+ \frac{\mu_{SH}}{2} \left[ S^\dagger H_1^\dagger H_2 + S H_1 H_2^\dagger \right] + \frac{\mu_{SH}^2}{2} \left[ S H_1^\dagger H_2 + S^\dagger H_1 H_2^\dagger \right],$$

together with the GUT scale boundary conditions

$$\mu_1^2 (M_G) > 0, \ \mu_2^2 (M_G) = \mu_3^2 (M_G) > 0,$$

$$\lambda_2 (M_G) = \lambda_S (M_G) = \lambda_{S2} (M_G), \ \lambda_3 (M_G) = \lambda_{S1} (M_G),$$

and

$$\mu_5^2, \ \mu_{SH}^2 \lesssim O \left( \frac{M_G}{M_P} \right)^n \mu_{1,2}^2,$$

$$\lambda_5, \ \lambda_{S1}, \ \lambda_{S2}, \ \lambda_6 \lesssim O \left( \frac{M_G}{M_P} \right)^n \lambda_{1,2,3,4}.$$

While the parameters in Eq.(3) are allowed by $SO(10)$, the ones in Eq.(4) can be generated only after $SO(10)$ breaking by operators suppressed by $n$ powers of the Planck scale $M_P$. Because

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$^3$An alternative possibility to introduce non-supersymmetric DM using the general idea of non-supersymmetric matter-parity $P_M$ proposed in [5] is to introduce $P_M$-even fermion multiplets of $SO(10)$ [19].
the low scale particle mass spectrum is obtained from a small number of parameters at \( M_G \) via RGE running \([6]\), this scenario is called constrained scalar DM model in a direct analogy with the constrained MSSM.

The charged Higgs boson mass coming from Eq.\((2)\) is given by

\[
m_{H^+}^2 = \mu_2^2 + \lambda_3 v^2/2,
\]

and the neutral \( P_M \)-odd scalar masses \( m_{1,2}^2 \) are obtained by diagonalization of the mass matrix

\[
m^2 = \begin{pmatrix}
\mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2/2 & (\mu_{SH} + \mu_{SH}^\prime) v/(2\sqrt{2}) \\
(\mu_{SH} + \mu_{SH}^\prime) v/(2\sqrt{2}) & \mu_3^2 + \mu_5^2 + (\lambda_{S1} + \lambda_{S1}) v^2/2
\end{pmatrix}.
\]

The pseudo-scalar masses \( m_{3,4}^2 \) are obtained from \( m_{1,2}^2 \) by replacing \( \lambda_5 \to -\lambda_5 \), \( \lambda_{S1} \to -\lambda_{S1} \), \( \mu_5^2 \to -\mu_5^2 \). For clarity we denote the lightest neutral scalar by \( S_{\text{DM}} \) and the next-to-lightest neutral scalar by \( S_{\text{NL}} \).

We note that the mass degeneracy of \( S_{\text{DM}} \) and \( S_{\text{NL}} \) is a generic prediction of the scenario and follows from the underlying \( SO(10) \) gauge symmetry via Eq.\((4)\). This degeneracy has several phenomenological implications which allow one to discriminate this scenario from other DM models. For example, it implies long lifetime for \( S_{\text{NL}} \) which provides clear experimental signature of displaced vertex in the decays \( S_{\text{NL}} \to S_{\text{DM}} \ell^+ \ell^- \) at the LHC \([18]\). In the context of present work the decays of \( S_{\text{NL}} \) occur in the chain of \( H^\pm \) decays and allow one to distinguish \( H^\pm \) over the SM background.

At \( M_G \) the SM gauge symmetry may not be spontaneously broken, \( \mu_1^2(M_G) > 0 \). To obtain successful EWSB at low energies the parameter \( \mu_1^2(M_Z) \) can become negative either by the RG evolution \([6]\) or via the Coleman-Weinberg-like \([20]\) EWSB mechanism \([13, 14]\). Thus in the constrained scalar DM model the EWSB may occur dynamically due to the existence of dark scalar couplings to the SM Higgs boson. In the following we study two scenarios of the CSDMM, one with explicit EWSB as in the SM, and one with radiative EWSB due to DM RG effects in the scalar sector.

### 3 Inert charged Higgs boson phenomenology at LHC

Compared to the 2HDM models, inert \( H^\pm \) production lacks the primary parton level process \( b\bar{b} \to H^+H^- \) with a top quark in the \( t \)-channel and the secondary production processes through the decays \( t \to H^+b \). The only available production processes are depicted in Fig.\([1]\). Because of the matter-parity conservation, the inert charged Higgs can only decay into an odd (usually one) number of dark scalars plus SM particles, see Fig.\([2]\). Thus the 2HDM decays like \( H^+ \to W^+H^0 \) or \( H^+ \to t\bar{b} \) cannot take place. We are going to show that those features allow to discover matter-parity-odd charged Higgs boson at the LHC.
3.1 Direct production

The main parton level production processes for the inert charged scalars at the LHC are (see Fig.1):

\[ q\bar{q} \rightarrow \gamma^*/Z^* \rightarrow H^+H^-, \quad (7a) \]

\[ q'q' \rightarrow W^\pm \rightarrow S_iH^\pm, \quad (7b) \]

\[ gg \rightarrow h^* \rightarrow H^+H^-, \quad (7c) \]

where \( S_i \) stands for the new \( P_M \)-odd neutral scalars and \( h \) is the SM Higgs boson. The processes (7a) and (7b) have previously been studied in Refs. [15, 16]. We present details of calculating cross sections of those processes for completeness. Studies of the process (7c), which is the dominant production channel for light charged Higgs, is a new result of this paper. The process (7c) is proportional to the single parameter \( \lambda_3 \) in Eq.(2) and allows one to measure that parameter at the LHC experiments. We note that the process \( gg \rightarrow \gamma^*/Z^* \rightarrow H^+H^- \) vanishes identically because of the assumed CP invariance (see for instance [21]).

We start with discussing the process (7a). Its parton level cross section is given by

\[
\sigma_{q\bar{q} \rightarrow H^+H^-} = \frac{e^4}{768\pi c_W^2 s_W^4} \frac{(\hat{s} - 4M_{H^\pm}^2)}{s^{9/2} \sqrt{s - 4m_q^2 (M_Z^2 - \hat{s})^2}} \times \left[ a_q^2 \hat{s}^2 (c_W^2 - s_W^2) (4m_q^2 - \hat{s}) - (2m_q^2 + \hat{s}) (4q_q c_W^2 s_W \hat{s} - M_Z^2) + v_q \hat{s} (c_W^2 - s_W^2) \right]^{3/2}, \tag{8}
\]

Figure 1: Feynman diagrams for inert charged Higgs boson production at the LHC.

Figure 2: Feynman diagram for the inert \( H^+ \) decays into dark scalars \( S_i \) and two fermions.
Finally we study the process (7c). The Feynman amplitude of that process is given by

$$\sigma_{q\bar{q} \rightarrow H^+H^-} = \int dx_a dx_b [q_a(x_a)\bar{q}_b(x_b) + q_b(x_b)\bar{q}_a(x_a)]\sigma_{q\bar{q} \rightarrow H^+H^-}. \quad (9)$$

For the process (7b) the corresponding parton level cross section is

$$\sigma_{q'\bar{q}' \rightarrow S^+} = \sigma_{q'\bar{q}' \rightarrow S^+} = \frac{\eta_i^2}{1536\pi} \left(\frac{e}{s_W}\right)^4 \times$$

$$\times \left(M_{H^+}^4 - 2M_{H^+}^2 (M_{S^+}^2 + \hat{s}) + (M_{S^+}^2 - \hat{s})^2\right)^{3/2} \left(2\hat{s}^2 - \hat{s} (m_q^2 + m_{q'}^2) - (m_q^2 - m_{q'}^2)^2\right) \hat{s}^3 (M_W^2 - \hat{s})^2 \sqrt{-2\hat{s} (m_q^2 + m_{q'}^2) + (m_q^2 - m_{q'}^2)^2 + \hat{s}^2}, \quad (10)$$

where $q(q')$ means up(down)-type quark and $M_W$ is the $W$ boson mass. Notice that the cross section (10) depends on the nature of the final state neutral scalar $S_i$. If the outgoing scalar is singlet-like one has $\eta_i = s$, where $s$ is the sine of the small singlet-doublet mixing angle, and the cross section (10) is very much suppressed. If, however, the outgoing scalar is doublet-like, $\eta_i = c$ is of order unity. Since the process with an outgoing $H^+$ is the conjugate of the process with an outgoing $H^-$, the corresponding parton level cross sections are equal. However, the observable cross sections in $pp$ collisions at the LHC are different because of the different parton structure functions for up and down type quarks,

$$\sigma_{pp \rightarrow S^+} = \int dx_a dx_b [q_a(x_a)\bar{q}_b(x_b) + q_b(x_b)\bar{q}_a(x_a)]\sigma_{q\bar{q} \rightarrow S^+}, \quad (11)$$

$$\sigma_{pp \rightarrow S^-} = \int dx_a dx_b [q_a(x_a)\bar{q}_b(x_b) + q_b(x_b)\bar{q}_a(x_a)]\sigma_{q'\bar{q}' \rightarrow S^-}. \quad (12)$$

Finally we study the process (7c). The Feynman amplitude of that process is given by

$$|M_{gg \rightarrow H^+H^-}|^2 = L^2 \left(\frac{\lambda_3 v}{\hat{s} - M_h^2}\right)^2, \quad (13)$$

where $M_h$ is the Higgs boson mass, $\lambda_3 v$ is the trilinear scalar self-coupling, and the loop factor $L$ is given by [22]

$$L^2 = \frac{\alpha_s}{8\pi^2 v} \left|\sum_q F_q\right|^2, \quad F_q = -(2m_q)^2 \left[1 + (1 - \tau) f(\tau)\right],$ \quad (14)$$

where

$$f(\tau) = \begin{cases} \sin^{-1}\left(\sqrt{1/\tau}\right)^2, & \tau \geq 1 \\ -\frac{1}{4} \log\left(1 + \frac{\sqrt{1 + 1/\tau}}{1 - \sqrt{1 + 1/\tau}}\right) - i\pi, & \tau < 1 \end{cases}, \quad \tau = \frac{(2m_q)^2}{\hat{s}}. \quad (15)$$
Figure 3: Cross-sections for $pp \to H^+H^-$ via $q\bar{q}$ (red), $pp \to H^+H^-$ via $gg$ (blue), $pp \to S_{\text{DM,NL}}H^+$ (green) and $pp \to S_{\text{DM,NL}}H^-$ (black) at the LHC for $\sqrt{s} = 14$ TeV without (left panel) and with (right panel) radiative EWSB mechanism.

The corresponding parton level cross section reads

$$\sigma_{gg\to H^+H^-} = \frac{\alpha_S (\lambda_3 v)^2}{1152\sqrt{2} \pi^3} \left| \sum_q F_q \right|^2 \frac{\sqrt{(-2M_{H^\pm}^2 + s)^2 - 4M_{H^\pm}^4}}{s^2v^2(\hat{s} - M_h^2)^2},$$

while the integrated cross section is found via

$$\sigma_{gg\to H^+H^-}^{gg} = \int dx_a dx_b \left[ g_a(x_a)g_b(x_b) + g_b(x_b)g_a(x_a) \right] \sigma_{gg\to H^+H^-},$$

where $g(x)$ is the gluon density function.

We computed the cross sections of the processes (7a), (7b) and (7c) in $pp$ collisions at the LHC by convoluting over the parton distribution functions of Ref. [23]. We scan over the parameter space of the model and select out the parameters that imply the observed amount of DM, $0.094 < \Omega_{\text{DM}} < 0.129$, in thermal freeze-out at early Universe. The DM abundance is calculated with MicrOMEGAs package [24]. As already explained, we consider separately the scenarios with and without radiative EWSB mechanism.

Fig. 3 shows the scatter plots of the $H^+H^-$, $S_{\text{DM,NL}}H^+$ and $S_{\text{DM,NL}}H^-$ production cross sections in $pp$ collisions at the LHC for the collision energy $\sqrt{s} = 14$ TeV as a function of charged Higgs mass. The colour code is explained in the caption. Because $S_{\text{DM}}$ and $S_{\text{NL}}$ are almost degenerate, their production cross sections are almost equal. The results of a general scan are presented in the left panel of Fig. 3. In the right panel of the same figure successful EWSB is required to occur due to the RGE effects of the SM Higgs boson couplings to the DM sector. One sees that no light charged Higgs ($M_{H^\pm} \lesssim 150$ GeV) is permitted in the latter case. For the light $H^\pm$, the loop level gluon-gluon production process dominates over the tree level Drell-Yan processes only in the general case. In that case the parameter $\lambda_3$ can be directly derived from the cross section measurement, see Eq. (13). If one also requires radiative EWSB from the DM couplings, the former process is somewhat suppressed by the higher SM Higgs boson mass coming from the lower bound $M_H > 130$ GeV from the vacuum stability argument [18].
Fig. 3 demonstrates that for heavy $H^\pm$ the sub-process (7a) always dominates. However, the cross section of this process is fully determined by the gauge couplings and depends only on the mass of charged Higgs boson. Therefore one can reliably calculate the cross section of the sub-process (7a) and to split the experimentally measured $H^+H^-$ pair production cross section between the two dominant contributions (7a) and (7c).

3.2 Long-lived $H^\pm$ in the constrained scalar DM scenario

With the integrated luminosity 100 fb$^{-1}$ and low $H^\pm$ mass the LHC can produce thousands of $H^+H^-$ pairs. In this scenario the mass difference between the charged Higgs and the dark matter scalar turned out to be less than the $W$ mass and the decays with on-shell $W$ or $Z$ in the final state are kinematically forbidden. At the leading order the only kinematically allowed decays are (see Fig. 2)

$$H^\pm \rightarrow S_i f f',$$

where $S_i$ stands for any of the four neutral $P_M$-odd scalars and $f, f'$ denote the SM leptons or quarks. In most of the cases the only kinematically allowed decays of $H^\pm$ are to the lightest states $S_{DM}$ and $S_{NL}$. Because those states are almost degenerate in mass due to the GUT gauge symmetry, see Eq.(4), the $H^\pm$ branching ratios to those states are practically equal. Thus, if $S_i \equiv S_{DM}$ in (18), the resulting experimental signatures of the $H^+H^-$ production include $\ell^+\ell^-, jjjj$ or $\ell^±jj$ final states plus missing $E_T$. Unfortunately those experimental signatures cannot be seen over the huge $W^+W^-$ background [15, 16] unless some new distinctive feature occurs which allows to suppress the background. We claim in this work that the distinctive feature might be macroscopically long $H^\pm$ lifetime. However, if $S_i \equiv S_{NL}$ in (18) that happens with almost equal probability, the above described experimental signatures are going to be supplemented by the decays $S_{NL} \rightarrow S_{DM} f \bar{f}$ which necessarily must have a displaced $\ell^+\ell^-$ or $jj$ vertex due to the $S_{DM,NL}$ mass degeneracy [18]. In the latter case the experimental signature of the $H^+H^-$ pair production includes two additional displaced $\ell^+\ell^-$ or $jj$ vertices.

Unlike in the inert doublet model [15, 16], in the constrained scalar DM model the lightest dark scalar is predicted to be dominantly singlet by RG evolution of the model parameters. As already mentioned, the charged Higgs and the DM masses, given by Eq.(5) and Eq.(6), respectively, turned out to be close to each other in a wide range of the parameter space. Therefore the $H^\pm$ decays are suppressed by two factors (i) by the sine of singlet doublet mixing angle, $\eta = s$; (ii) by the (possibly) small mass difference $\Delta M = M_{H^\pm} - M_{S_i} > m_f + m_{f'}$. Indeed, the decay rate of Eq.(18) is given by

$$\Gamma_{H^\pm \rightarrow S_i f f'} = \frac{1}{32 M_{H^\pm}^3} \int_{m^2_{12}^{\min}}^{m^2_{12}^{\max}} \int_{m^2_{23}^{\min}}^{m^2_{23}^{\max}} \left| M_{H^\pm \rightarrow S_i f f'} \right|^2, \quad (19)$$

where $m_{12}$ and $m_{23}$ are kinematic variables defined as

$$m^2_{12} = M^2_{H^\pm} + m_f^2 - 2M_{H^\pm}E_f,$$
$$m^2_{23} = M^2_{H^\pm} + M^2_{S_i} - 2M_{H^\pm}E_{S_i}, \quad (20)$$

$$m^2_{12} = M^2_{H^\pm} + m_f^2 - 2M_{H^\pm}E_f,$$
$$m^2_{23} = M^2_{H^\pm} + M^2_{S_i} - 2M_{H^\pm}E_{S_i}, \quad (21)$$

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and the integration limits are given by

\[ m_{12}^{\text{max}} = (M_{H^\pm} - m_f)^2, \]
\[ m_{12}^{\text{min}} = (M_{S_i} + m_{f'})^2, \]

and

\[ m_{23}^{\text{max}} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^{*2} - m_{f'}^2} - \sqrt{E_3^{*2} - m_f^2} \right)^2, \]
\[ m_{23}^{\text{min}} = (E_2^* + E_3^*)^2 - \left( \sqrt{E_2^{*2} - m_{f'}^2} + \sqrt{E_3^{*2} - m_f^2} \right)^2. \]

Here

\[ E_2^* = \frac{m_{12}^2 - M_{S_i}^2 + m_{f'}^2}{2m_{12}}, \]
\[ E_3^* = \frac{M_{H^\pm}^2 - m_{12}^2 - m_f^2}{2m_{12}}, \]

and \( m_f, m_{f'} \) are the outgoing fermion masses.

The Feynman amplitude of the decay, \( M_{H^+ \rightarrow S_i f\bar{f}'} \), is proportional to \( \eta_i = s \) if the outgoing scalar is singlet-like (usually this is the lightest state) or to \( \eta_i = c \) if the outgoing scalar is doublet-like where \( s(c) \) is the sine (cosine) of the mixing angle of the new scalar states. The model dependence enters in the value of the \( \eta_i \) parameter and in the number of \( S_i \) possible states: two for an inert doublet model \[15, 16\], four for our model.

Fig. 4 shows model independent contour plots for (the distance \( \ell \) x (the sine of singlet-doublet mixing angle squared, \( \eta_i^2 \))) travelled by \( H^\pm \) as a function of the dark matter mass \( M_{DM} \) and the mass gap \( \Delta M = M_{H^\pm} - M_{DM} \). In the left panel we consider large values for \( \Delta M \) while in the right panel we assume \( \Delta M < 8 \text{ GeV} \). One can see that, in order to get a macroscopic displaced vertex (for instance \( \ell \gtrsim 1 \text{ mm} \)), one needs both small values for the mixing parameter \( \eta_i^2 \) and the small mass gap. However, the latter needs not to be fine tuned to extreme values, the mass gap of several GeV is quite natural.

Fig. 5 shows the distance of displaced vertex in inert \( H^\pm \) decays from the interaction point for the same parameter points as in Fig. 3. Even if the distance is usually microscopic, for large region in the parameter space the charged Higgs displaced vertex can be measured at the LHC experiments. In some cases \( H^\pm \) are so long-lived that they may decay outside the detector. In such cases DM is strongly singlet-like, that means \( \eta \rightarrow 0 \) and there is an accidental degeneracy between \( H^\pm \) and \( S_{DM} \). Those two experimental signatures are theoretically SM background-free and allow \( H^\pm \) to be discovered at the LHC up to the masses \( M_{H^\pm} \lesssim \mathcal{O}(300) \text{ GeV} \). The latter estimate is based on our calculation of the production cross sections and decay branching ratios and should be quantified with a detailed detector level simulation which is beyond the scope of this work.

If the only available decay modes of \( H^\pm \) are \( H^\pm \rightarrow S_{DM} f f' \) and \( H^\pm \rightarrow S_{NL} f f' \), one has \( BR(H^\pm \rightarrow S_{DM} f f') = BR(H^\pm \rightarrow S_{NL} f f') \) and the branching ratios can be obtained just by
Figure 4: The distance $\ell$ travelled by $H^\pm$ times $\eta_i^2$ for $E_{H^\pm} = 1$ TeV as a function of the DM mass $M_{DM}$ and the mass gap $\Delta M = M_{H^\pm} - M_{DM}$.

Figure 5: Distance of $H^\pm$ displaced vertex from the interaction point as a function of its mass $M_{H^\pm}$ for $E_{H^\pm} = 1$ TeV. In the left panel radiative EWSB due to DM is not required while in the right panel the radiative EWSB is required to occur. The region between dashed lines is the CMS tracker radius.
counting the available light SM quarks and leptons in the final state. However, if the decays to the heavier neutral scalar states $S_{3,4}$ become kinematically available the branching ratios to different decay channels are highly model dependent. This happens when the mass splitting between the DM and $H^\pm$ becomes large.

We plot in Fig. 6 the sum of branching ratios $BR(H^\pm \rightarrow S_{DM} \ell^+ \nu)$ into the leptonic final states $\ell = e, \mu$ as a function of $M_{H^+}$ and $\Delta M$. The branching ratios are expressed with the colour code as explained in the caption. The red points confirm what we discussed in the previous paragraph: for small mass splitting only the decays into $S_{DM}$ final state are possible and the branching ratio is essentially constant depending on the available SM fermions in the final state. However, for large $\Delta M$ the branching ratio $BR(H^\pm \rightarrow S_{DM} \ell \nu)$ may vary in a considerably wide range.

4 Benchmark points for the constrained scalar DM model

To study the charged inert Higgs boson pair production at the LHC we propose three benchmark points with a distinctive phenomenology. The points are summarized in Table 1. In all points the charged Higgs is long-lived, the pair production cross section is large and the correct amount of predominantly singlet DM is produced in thermal freeze-out at early Universe.

In the case of points P1 and P2, inert $H^\pm$ decays inside the tracker of the LHC experiment. The experimental signature of those points is that the charged track of $H^\pm$ breaks into a charged lepton track and missing energy. This is theoretically a background-free signature. The main feature of P1 is that $H^\pm$ mass is below the radiative EWSB threshold. If such a light $H^\pm$ is discovered, the EW symmetry must be broken explicitly.

In the case of P2 the pair production cross section is dominated by the sub-process $7c$ which
Table 1: Benchmark points for the inert charged Higgs boson phenomenology at the LHC. The masses are given in units of GeV, the cross sections in fb and the length \( \ell \) in mm.

is proportional to the single parameter \( \lambda_3 \). Because the cross section of (7a) depends only on the \( H^\pm \) mass, its contribution to the total cross section can be computed accurately. Therefore, in the case of P2 the measurement of \( H^\pm \) pair production cross section at the LHC implies a measurement of \( \lambda_3 \) with a high accuracy. Because in this point EWSB occurs radiatively due to RG effects, the measurement of \( \lambda_3 \), together with the mass determination via Eq.(5), offers a consistency check of the model.

In the case of P3 the inert \( H^\pm \) is so long-lived that it crosses the tracker of the LHC experiment completely and decays outside the detector. This case can be discovered by a slow charged track of \( H^\pm \). Thus the phenomenology of P3 resembles the phenomenology of charged R-hadron [25] rather than that of the charged Higgs boson. However, its production cross section is determined by weak interactions not by the strong interaction as in the case of a typical R-hadron.

5 Conclusions

We have studied the inert charged Higgs boson production at the LHC in the context of constrained scalar DM model. The previous similar works, performed in the context of inert doublet model, have shown that the \( H^+H^- \) final states cannot be seen at the LHC over the huge \( W^+W^- \) background. However, the inert doublet model is just one particular limit of a general matter-parity induced scalar DM scenario. In the constrained scalar DM model studied in this work the lightest DM scalar is predicted to be predominantly singlet. Due to the small singlet-doublet mixing the \( H^\pm \) lifetime can be macroscopically long if, in addition, the charged Higgs and the DM particle have a small mass difference.

We have recomputed the \( H^+H^- \), \( H^\pm S_i \) production cross sections in \( pp \) collisions at the LHC. We have included a gluon-gluon one-loop contribution depicted in Fig. 1 and shown that it actually dominates the total cross section for light \( H^\pm \). We have required the production of correct amount of DM of the Universe in thermal freeze-out and analyzed this scenario in two distinctive cases: when the EWSB occurs radiatively due to the DM interactions with the SM Higgs boson and when EW symmetry is broken explicitly. We show that in an appreciable part of the parameter space \( H^\pm \) can be long-lived and decay via (18) at a macroscopic distance from the interaction point. This signature is theoretically background-free and allows \( H^+H^- \) to be discovered at the LHC up to the masses \( M_{H^\pm} \lesssim O(300) \) GeV. To test this scenario we have proposed three benchmark points with different charged Higgs phenomenology. If, however, \( H^\pm \) are short-lived, their decays to the next-to-lightest neutral scalar, namely \( H^\pm \rightarrow S_{NL}ff' \),
will be followed by the decays $S_{NL} \to S_{DM} f \bar{f}$. In the latter case the experimental signatures of the $H^+H^-$ pair production include two additional displaced $\ell^+\ell^-$ or $jj$ vertices. Those unique experimental signatures allow one to discover the inert charged Higgs over the SM background at the LHC.

The numerical estimates in this paper are based on our theoretical calculations of the production cross sections and decay branching ratios and should be quantified with a detailed detector level simulation which is beyond the scope of this work.

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