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New signals for doubly-charged scalars and fermions at the Large Hadron Collider

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Several extensions of the standard model have light doubly charged Higgs bosons in their particle spectrum. The supersymmetric versions of these models introduce fermionic superpartners of these doubly charged Higgs bosons, the Higgsinos, which also remain light. In this work we analyze a new collider signal resulting from the pair production and decay of a light doubly charged Higgsino to an even lighter doubly charged Higgs boson. We focus on the minimal left-right supersymmetric model with automatic R-parity conservation, which predicts such a light doubly charged Higgs boson and its Higgsino partner at the TeV scale, which are singlets of $SU(2)_L$. We investigate the distinctive signatures of these particles with four leptons and missing transverse energy in the final state at the Large Hadron Collider and show that the discovery reach for both particles can be increased in this channel.

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I. INTRODUCTION

Several extensions of the standard model (SM) predict the existence of doubly charged Higgs bosons. In some cases these particles remain light, which motivates searches for them in high energy collider experiments. The minimal left-right supersymmetric model with automatic R-parity conservation is an example, where a light doubly charged Higgs boson arises as a pseudo-Goldstone boson of the $SU(2)_R$ gauge symmetry breaking [1–4]. Models with radiative neutrino mass generation [5], type II seesaw mechanism [6] for small neutrino masses, and the 3-3-1 model [7] are some other examples of SM extensions that have doubly charged Higgs bosons. Supersymmetric versions of these models also have doubly charged Higgsinos, which are the fermionic partners of the Higgs bosons. If the doubly charged Higgs boson is light, its Higgsino partner cannot be much heavier and must have mass of the order a few hundred GeV to a few TeV, in the context of low energy supersymmetry (SUSY).

In this paper we study a new signal for the doubly charged Higgs bosons and Higgsinos in SUSY models that arises through the pair production of the doubly charged Higgsinos. Each Higgsino decays into a doubly charged Higgs boson and the lightest supersymmetric particle (LSP), which escapes detection. Thus the final state would have four leptons and missing transverse energy, with the same-sign dileptons originating from the decays of the doubly charged Higgs bosons showing characteristic peaks in the invariant mass distribution. We show by detailed calculations in the context of the left-right supersymmetric model that the reach at the LHC for both these doubly charged particles can be enhanced by studying this mode. While we focus on the minimal supersymmetric left-right model, these new signals should also be present in other SUSY models with a light doubly charged Higgsino and a lighter doubly charged Higgs boson.

The focus of our analysis will be the minimal supersymmetric left-right gauge model. Left-right symmetric models [8] have a number of attractive features that are not naturally present in the standard model. First, it explains the small neutrino masses through the seesaw mechanism [9] in a compelling manner—unlike the SM, existence of right-handed neutrinos is required by gauge symmetry here. Second, it provides a natural understanding of the origin of parity violation as a spontaneous phenomenon [8]. Third, with the inclusion of supersymmetry, this model solves the gauge hierarchy problem and, in its simplest version, also provides an automatic R-parity. This symmetry arises as a remnant of the $(B-L)$ gauge symmetry [10] and leads to a stable light supersymmetric particle that can be a candidate for dark matter. With supersymmetry, these models also provide natural solutions to the strong CP problem and the SUSY CP problem [11].

In the minimal left-right supersymmetric model, the gauge group is extended to $G_{3221} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The $SU(2)_R \times U(1)_{B-L}$ symmetry breaks at a high scale resulting in most of the new particles getting very heavy masses. The right-handed neutrino mass is at this scale and facilitates the generation of the light neutrino mass via the seesaw mechanism. The doubly charged Higgs supermultiplet, on the other hand, remains light and can produce new signals, which is the focus of our analysis in this paper.

To understand why the doubly charged Higgs boson remains light in the minimal model, we need to look at the symmetry breaking sector. To spontaneously break the $SU(2)_R$ gauge symmetry and to generate large Majorana

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mass for the right-handed neutrino, we need to introduce a Higgs multiplet with quantum numbers $(1, 1, 3, -2)$ under the group G_{3221}. This right-handed triplet contains three complex fields: a doubly charged, a singly-charged and a neutral field denoted by $\delta^{c^{--}}$, $\delta^{c^{-}}$, $\delta^{c^{0}}$, respectively. The $\delta^{c^{-}}$ and the phase of $\delta^{c^{0}}$ are absorbed by the gauge fields via the super-Higgs mechanism to generate masses for the $W_R^{\pm}$ and Z_R gauge bosons. The real part of $\delta^{c^{0}}$ gets a mass through the Higgs potential. The $\delta^{c^{--}}$ field, on the other hand, is not absorbed by any gauge bosons, nor does it acquire a mass from the superpotential of the minimal model. Thus it behaves like pseudo-Goldstone boson, acquiring its mass only after supersymmetry breaking.[1] As a result, the right-handed doubly charged Higgs bosons and the doubly charged Higgsinos remain light in this model.

The doubly charged Higgs bosons decay to two same charge leptons, which can be seen relatively easily in collider experiments via the invariant mass peak in the dilepton mass spectrum. LHC has been looking for signals of doubly charged Higgs boson in the four-lepton final states [12,13]. The experimental lower limit inferred on the mass of such Higgs bosons would depend on the assumed branching ratios into leptons of definite flavors. For example, CMS experiment quotes a 95% CL lower limit of 355 GeV for the mass of a doubly charged Higgs boson arising from an $SU(2)_L$ triplet, if it decays with equal branching ratios of 33% into e^+e^+, $\mu^+\mu^+$ and $\tau^+\tau^+$. The 95% CL lower limit on such a Higgs particle from the ATLAS experiment is 318 GeV. These limits are somewhat weaker for an $SU(2)_L$ singlet doubly charged Higgs boson, since its production cross section is smaller compared to the case when it is a $SU(2)_L$ triplet. For example, ATLAS Collaboration quotes a lower limit on the mass of an $SU(2)_L$ singlet doubly charged scalar that decays with a 33% BR into $\mu^+\mu^+$ of about 220 GeV, while the limit is about 210 GeV if it decays into e^+e^+ with the same branching ratio. We anticipate that the lower limit, when both modes are combined, would be somewhat smaller than 300 GeV, for an $SU(2)_L$ singlet, as in our case.[2]

The decay of doubly charged Higgsino ($\tilde{\delta}^{c^{\pm\pm}}$) through a doubly charged Higgs boson ($\delta^{c^{\pm\pm}}$) can produce new signals through the following process:

$$\tilde{\delta}^{c^{\pm\pm}} \longrightarrow \delta^{c^{\pm\pm}} \tilde{\chi}_1^0 \longrightarrow l^{\pm} l^{\pm} \tilde{\chi}_1^0.$$

So the pair production of doubly charged Higgsinos yields a final state consisting of four leptons and missing transverse energy due to the LSP escaping the detector. This process, which has not been explored before to the best of our knowledge, gives a unique collider signature which can help improve the discovery reach of doubly charged particles. The invariant mass plot would show a peak at the doubly charged Higgs mass for the same-sign lepton while there would be no such peak for opposite-sign leptons. The angular distributions for the final state leptons also show a peak at a low value of ΔR (defined later in the paper) for same-sign leptons while the opposite-sign leptons have a peak at a much higher value. Using these distributions we can probe deeper into the model than one could just by looking at the pair production of the doubly charged Higgs bosons. The cross section for pair production of doubly charged Higgsinos is larger compared to the cross section for the pair production of doubly charged Higgs bosons of the same mass. From the current data at the LHC, we expect around 30 events for the process discussed in this paper, if the doubly charged Higgs boson has a mass of about 500 GeV, and if it decays into a doubly charged Higgs boson of mass around 300 GeV.

In Sec. II we describe the model and the Lagrangian needed for our analysis. We also explain the origin of masses of the doubly charged Higgs boson and the Higgsino and show that they remain light. In Sec. III, we present our analysis of the production and decay of the doubly charged scalars and fermions and give the collider signatures which can be observed at the LHC. Section IV gives a discussion of the results that we have obtained and how we can distinguish our signal against the background.

II. A BRIEF REVIEW OF THE LEFT-RIGHT SUPERSYMMETRIC MODEL

In this section, we briefly review the relevant features of the minimal supersymmetric left-right model (LRSUSY) necessary for the analysis which follows in the later sections [1,4].[3] The chiral matter in LRSUSY consists of three families of quark and lepton superfields,

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim \left(3, 2, 1, \frac{1}{3}\right), \quad Q^c = \begin{pmatrix} d^c \\ -u^c \end{pmatrix} \sim \left(3^*, 1, 2, -\frac{1}{3}\right),$$
$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (1, 2, 1, -1), \quad L^c = \begin{pmatrix} e^c \\ -\nu^c \end{pmatrix} \sim (1, 1, 2, 1), \tag{1}$$

where the numbers in the brackets denote the quantum numbers under $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge groups.

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[1] The superpotential of the model, which only has quadratic mass terms, has an enhanced global $U(3, c)$ [complexified $U(3)$] symmetry which is broken to an $U(2, c)$ by the vacuum expectation value (VEV) of this Higgs multiplet. This leads to five massless superfields of which three are absorbed to give mass to the heavy gauge bosons and the remaining are the two doubly charged Higgs bosons. Since SUSY is unbroken at this stage, the doubly charged Higgsino is degenerate with the doubly charged Higgs boson.

[2] When an $SU(2)_L$ singlet doubly charged Higgs boson decays 100% of the time into $\mu^+\mu^+$ (or e^+e^+), the ATLAS lower limit on its mass is about 310 (or 320) GeV [13].

[3] For alternative versions of SUSY left-right model, see Ref. [14].

The minimal Higgs sector consists of the following superfields:

$$
\begin{aligned}
\Delta(1,3,1,2) &= \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}, \\
\bar{\Delta}(1,3,1,-2) &= \begin{pmatrix} \frac{\overline{\delta}^-}{\sqrt{2}} & \overline{\delta}^0 \\ \overline{\delta}^{--} & -\frac{\overline{\delta}^-}{\sqrt{2}} \end{pmatrix}, \\
\Delta^c(1,1,3,-2) &= \begin{pmatrix} \frac{\delta^{c^-}}{\sqrt{2}} & \delta^{c^0} \\ \delta^{c^{--}} & -\frac{\delta^{c^-}}{\sqrt{2}} \end{pmatrix}, \\
\bar{\Delta}^c(1,1,3,2) &= \begin{pmatrix} \frac{\overline{\delta}^{c^+}}{\sqrt{2}} & \overline{\delta}^{c^{++}} \\ \overline{\delta}^{c^0} & -\frac{\overline{\delta}^{c^+}}{\sqrt{2}} \end{pmatrix}, \\
\Phi_a(1,2,2,0) &= \begin{pmatrix} \phi^+ & \phi_2^0 \\ \phi_1^0 & \phi_2^- \end{pmatrix}_a (a = 1,2), \qquad S(1,1,1,0).
\end{aligned} \tag{2}
$$

The Δ^c and $\bar{\Delta}^c$ fields are the right-handed triplets and are necessary for breaking the $SU(2)_R \times U(1)_{B-L}$ symmetry without inducing any R-parity-violating couplings. The Δ and $\bar{\Delta}$ fields are their left-handed partners, which are required for parity invariance. The two bidoublets Φ_a are needed to give mass to the quarks and leptons and to generate the Cabibbo-Kobayashi-Maskawa mixings. The singlet S is there to make sure that the $SU(2)_R \times U(1)_{B-L}$ symmetry breaking occurs in the supersymmetric limit [4].

The superpotential of the model is given as

$$
\begin{aligned}
W = {} & Y_u Q^T \tau_2 \Phi_1 \tau_2 Q^c + Y_d Q^T \tau_2 \Phi_2 \tau_2 Q^c \\
& + Y_\nu L^T \tau_2 \Phi_1 \tau_2 L^c + Y_l L^T \tau_2 \Phi_2 \tau_2 L^c \\
& + i(f^* L^T \tau_2 \Delta L + f L^{c^T} \tau_2 \Delta^c L^c) + S[\mathrm{Tr}(\lambda^* \Delta \bar{\Delta} \\
& + \lambda \Delta^c \bar{\Delta}^c) + \lambda'_{ab} \mathrm{Tr}(\Phi_a^T \tau_2 \Phi_b \tau_2) - M_R^2] + W',
\end{aligned} \tag{3}
$$

where

$$
\begin{aligned}
W' = {} & [M_\Delta \mathrm{Tr}(\Delta \bar{\Delta}) + M_\Delta^* \mathrm{Tr}(\Delta^c \bar{\Delta}^c)] + \mu_{ab} \mathrm{Tr}(\Phi_a^T \tau_2 \Phi_b \tau_2) \\
& + M_S S^2 + \lambda_S S^3.
\end{aligned} \tag{4}
$$

Here $Y_{u,d}$ and $Y_{\nu,l}$ are the Yukawa couplings for quarks and leptons, respectively, and f is the Majorana neutrino Yukawa coupling matrix. This is the most general superpotential. R-parity is automatically preserved in this case, which is a consequence of $(B - L)$ being part of the gauge symmetry. Putting $W' = 0$ gives an enhanced $U(1)$ R-symmetry in the theory. Under this R-symmetry, Q, Q^C, L, L^C fields have a charge of $+1$, S has charge $+2$ and all other fields have charge zero with W carrying a charge of $+2$. Putting $W' = 0$ also helps in understanding the μ parameter of minimal supersymmetric standard model since it is induced as $\mu \sim \lambda' \langle S \rangle$ from Eq. (3), which is of the scale of SUSY breaking, as necessary. Setting $W' = 0$ would make the doubly charged left-handed and right-handed Higgsinos degenerate in mass since both masses are given by $\lambda \langle S \rangle$ [see Eq. (3)].[4]

The $SU(2)_R \times U(1)_{B-L}$ symmetry is broken at a large scale by giving a large vacuum expectation value to the right-handed triplet Higgs boson fields Δ^c and $\bar{\Delta}^c$. This generates a large right-handed neutrino mass, $M_{\nu^c} = 2 f v_R$, where v_R is the vacuum expectation value of the δ^{c^0} field which breaks the $SU(2)_R$ symmetry. This helps generate a small Majorana mass for the left-handed neutrino via the seesaw mechanism [9]. The bidoublets get VEVs of the order of electroweak symmetry breaking scale and generate the masses of the quarks and leptons. The singlet S gets a VEV of order the SUSY breaking scale, and helps solve the μ problem of the minimal supersymmetric standard model, assuming that $W' = 0$.

The terms in the Lagrangian which will be most essential for our calculation later are the gauge kinetic terms for the triplet superfields and the quarks and leptons. These terms will give us the interaction vertices between the Higgs boson fields and the gauge bosons as well as the the fermions and the gauge bosons [15]. The kinetic terms for the triplet scalar fields and the fermions are given by

$$
L = i \sum \mathrm{Tr}[\overline{q}_i \not{D} q_i] + \mathrm{Tr}[(D^\mu \Phi_i)^\dagger (D_\mu \Phi_i)] \tag{5}
$$

where $q_i = Q, Q^c, \tilde{\Delta}, \tilde{\bar{\Delta}}, \tilde{\Delta^c}, \tilde{\bar{\Delta}}^c$ and $\Phi_i = \Delta, \bar{\Delta}, \Delta^c, \bar{\Delta}^c$. The covariant derivatives are defined as

$$
\begin{aligned}
D_\mu Q &= \left[\partial_\mu - i \frac{g_L}{2} \vec{\tau} \cdot \vec{W}_{\mu L} - i \frac{g_V}{6} V_\mu \right] Q \\
D_\mu Q^c &= \left[\partial_\mu + i \frac{g_R}{2} \vec{\tau} \cdot \vec{W}_{\mu R} + i \frac{g_V}{6} V_\mu \right] Q^c \\
D_\mu \Delta &= \partial_\mu \Delta - i \frac{g_L}{2} [\vec{\tau} \cdot \vec{W}_{\mu L}, \Delta] - i g_V V_\mu \Delta \\
D_\mu \bar{\Delta} &= \partial_\mu \bar{\Delta} - i \frac{g_L}{2} [\vec{\tau} \cdot \vec{W}_{\mu L}, \bar{\Delta}] + i g_V V_\mu \bar{\Delta} \\
D_\mu \Delta^c &= \partial_\mu \Delta^c + i \frac{g_R}{2} [\vec{\tau} \cdot \vec{W}_{\mu R}, \Delta^c] + i g_V V_\mu \Delta^c \\
D_\mu \overline{\Delta^c} &= \partial_\mu \overline{\Delta^c} + i \frac{g_R}{2} [\vec{\tau} \cdot \vec{W}_{\mu R}, \overline{\Delta^c}] - i g_V V_\mu \overline{\Delta^c}.
\end{aligned} \tag{6}
$$

The covariant derivatives for $\tilde{\Delta}$, $\tilde{\bar{\Delta}}$, $\tilde{\Delta^c}$, $\tilde{\bar{\Delta}}^c$ have similar form as Δ, $\bar{\Delta}$, Δ^c, $\bar{\Delta}^c$, respectively.

We now turn to some details of the calculation of the masses of doubly charged Higgs boson [3,4,16,17] and the Higgsinos. This will show that these particles are indeed light and will help us in our analysis later on. In the context of type II seesaw mechanism without supersymmetry, signatures of doubly charged Higgs bosons at the LHC have been studied in Refs. [18,19] recently. The main

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[4] Keeping a nonzero W' term does not affect the right-handed particle spectrum, but the left-handed Higgsino becomes very heavy in this case and will not contribute to our new signal. We present results of our analysis with and without the left-handed doubly charged Higgsino in the light spectrum, so this effect can be disentangled.

difference in our study is the inclusion of the doubly charged Higgsino, which helps enhance the multilepton signals.

A. Doubly charged Higgs boson

The right-handed doubly charged Higgs boson mass-squared matrix is given at tree level as

$$M^2_{\delta^{++}} = \begin{pmatrix} -2g_R^2(|v_R|^2 - |\overline{v_R}|^2) - \frac{\overline{v_R}}{v_R} Y & Y^* \\ Y & 2g_R^2(|v_R|^2 - |\overline{v_R}|^2) - \frac{v_R}{\overline{v_R}} Y \end{pmatrix}, \tag{7}$$

where

$$Y = \lambda A_\lambda S + |\lambda|^2 \left(v_R \overline{v}_R - \frac{M_R^2}{\lambda} \right).$$

Solving for the squared mass, it can be seen that one of the eigenvalues is negative. Including the contribution from the one-loop correction to the mass, the eigenvalues become [4]

$$M^2_{\delta^{\pm\pm}} = \frac{-Y(|v_R|^2 + |\overline{v_R}|^2) \pm \sqrt{(|v_R|^2 + |\overline{v_R}|^2)^2 |4g_R^2 v_R \overline{v_R} - Y|^2 + 4|v_R|^2 |\overline{v_R}|^2 |Y|^2}}{2|v_R||\overline{v_R}|} + \mathcal{O}\left(\frac{M^2_{\mathrm{SUSY}}}{16\pi^2} \right), \tag{8}$$

where M_{SUSY} is the mass scale for the supersymmetry breaking which we assume to be ~ 1 TeV. The factor of $1/(16\pi^2)$ factor comes from the Coleman-Weinberg potential formula, which is used to calculate the one-loop correction. Explicit calculation of the effective potential utilizing the Majorana Yukawa couplings of the right-handed neutrino has shown that the eigenvalue that is negative at the tree-level can be made positive [4], thus making the symmetry breaking consistent. This makes the mass of the right-handed doubly charged Higgs boson to be of the electroweak scale, of order few hundred GeV. It is naturally lighter than the doubly charged Higgsino, since there is no loop suppression for its mass. This light doubly charged Higgs boson will be denoted as $\delta_R^{\pm\pm}$ in this paper.

A light doubly charged Higgs boson can also be obtained in left-right supersymmetric models which include nonrenormalizable operators in the superpotential [2]. Terms in the superpotential of the type $(\Delta^c \bar{\Delta}^c)^2/M_{\mathrm{Pl}}$ will give mass to the doubly charged Higgs bosons and Higgsinos of order few hundred GeV without resorting to the Coleman-Weinberg effective potential, provided that the $SU(2)_R$ breaking scale is in the range of $v_R \sim (10^{11}$–$10^{12})$ GeV. Our analysis will also be valid for these models with light doubly charged particles.

The left-handed doubly charged Higgs boson mass-squared matrix looks very similar to the right-handed case except that the VEVs of the right-handed neutral Higgs boson fields are now replaced by the VEVs of the left-handed fields which we assume to be negligible. Hence the mass of the left-handed doubly charged Higgs boson become of the order of M_R, which is of the scale of the $SU(2)_R$ symmetry breaking and hence large. This happens because in the Higgs boson potential, there is a cancellation between the terms $|\lambda|^2(v_R \overline{v}_R)$ and $\frac{M_R^2}{\lambda}$, arising from the vanishing of the F-terms, which is not present for the left-handed doubly charged Higgs boson mass-squared matrix. We will denote the left-handed doubly charged Higgs boson as $\delta_L^{\pm\pm}$.

B. Doubly charged Higgsino

The right-handed doubly charged Higgsino gets its mass only from the superpotential Eq. (3) and has the form $\lambda\langle S\rangle$. In the supersymmetric limit, $\langle v_R\rangle = \langle \overline{v}_R\rangle$ (which arises from the vanishing of the D terms) and $\langle S\rangle = 0$ (which arises from the vanishing of the F terms), and thus the Higgsino mass is zero in this limit. After supersymmetry breaking, the singlet S gets a VEV which is of the order of M_{SUSY}. Taking λ to be of order one, we see that its mass is at the SUSY breaking scale. Thus the Higgsino has to be relatively light if we consider supersymmetry to be broken at a scale of ~ 1 TeV.

The left-handed doubly charged Higgsino would become heavy if we turn on the W' term in the superpotential. In this paper we will consider $W' = 0$ and hence the left-handed and the right-handed doubly charged Higgsinos remain degenerate. However, the case of the left-handed Higgsino being heavy can be inferred from our results, since we separate out its contribution to the four-lepton-plus-missing-$\not{E}_T$ final states.

III. SIGNALS OF DOUBLY CHARGED SCALARS AND FERMIONS AT LHC

In this section we discuss the signal for doubly charged Higgsinos at the LHC and analyze the final states coming from the pair production of the doubly charged Higgsinos and their subsequent decay.[5] The doubly charged Higgsinos are pair-produced at the LHC through the process (illustrated in Fig. 1)

$$pp \to \tilde{\delta}^{++}_{L,R} \tilde{\delta}^{--}_{L,R},$$

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[5] The relevant Feynman rules are listed in the Appendix.

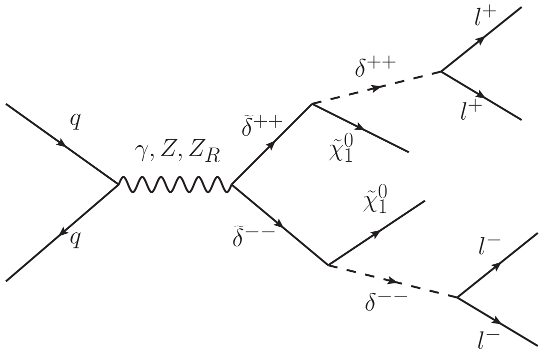

FIG. 1. Direct production of $\tilde{\delta}_R^{\pm\pm}$ pair at the LHC. Subsequent decays of $\tilde{\delta}_R^{\pm\pm}$ give rise to two leptons plus missing energy signal, if $M_{\delta_R^{\pm\pm}} < M_{\tilde{\delta}_R^{\pm\pm}}$.

which proceeds through s-channel γ and $Z_{L,R}$ exchanges [20]. As the mass of Z_R is dependent on the scale at which the $SU(2)_R$ is broken, its contribution will vary depending upon its allowed values. In the minimal left-right supersymmetric model, there is a relation between the W_R and the Z_R mass where $M_{Z_R} \sim 1.7 M_{W_R}$. Therefore the current limit on the W_R mass of about 2.5 TeV [21] requires the Z_R to be rather heavy. This heavy Z_R has very small contributions to the pair production cross section of the doubly charged Higgsinos. In our analysis we have fixed the Z_R mass at 5 TeV and find that the contributions from Z_R exchange only become comparable to the electroweak gauge boson exchanges for large values of the doubly charged Higgsino mass, where the overall signal is quite suppressed.

We focus on a natural scenario where the only "light" states beyond the SM are the doubly charged Higgs boson, doubly charged Higgsino and the lightest neutralino, which is the LSP. The left-handed doubly charged Higgsino is degenerate with the right-handed doubly charged Higgsino (in the case where $W' = 0$). All other SUSY particles are assumed to be much heavier. We further assume that the doubly charged Higgsino is heavier than the right-handed doubly charged Higgs boson and the lightest neutralino. Then the dominant decay channel for the doubly charged Higgsino is to the light doubly charged Higgs boson and the LSP neutralino, which we assume is allowed by kinematics. The branching ratio for this process is almost 1 in this scenario as the next leading decay mode is into a lepton and an off-shell slepton that is highly suppressed. The right-handed doubly charged Higgs boson now decays almost entirely into two same sign leptons giving rise to a final signal of four leptons and missing energy. Other decay modes of the right-handed doubly charged Higgs boson would be into two real or virtual W_R bosons or a W_R and a single-charged Higgs boson. Both the W_R and the single-charged Higgs boson are very heavy in this model and hence those decays will be forbidden or highly suppressed. The entire decay chain is then

(i) $\tilde{\delta}_R^{\pm\pm} \to \delta_R^{\pm\pm} \tilde{\chi}_1^0$
(ii) $\delta_R^{\pm\pm} \to \ell^\pm \ell^\pm$.

Though the right-handed doubly charged Higgsino decays almost always into a right-handed doubly charged Higgs boson and a neutralino, the left-handed doubly charged Higgsino which is degenerate with the right-handed doubly charged Higgsino cannot decay through this channel as the left-handed doubly charged Higgs boson is much heavier. The main decay channel for the left-handed Higgsino is then given by the three-body decay through an off-shell slepton and a lepton, where the off-shell slepton mediates the decay into a lepton and a neutralino [20]. This produces the same final state product as our signal and is therefore a source of background if we consider the signal coming only from the right-handed doubly charged Higgsinos. The left-handed doubly charged Higgsino production cross section is larger than the right-handed Higgsino due to the Z-boson coupling strength being larger to the left-handed particles and hence we also need to analyze the decay of the left-handed Higgsino and include its contributions. We must however note that both the right-handed and left-handed Higgsino pair production leads to a four-lepton final state with large missing transverse momenta because of the presence of the undetected LSP passing through the detector. Another source for the four-lepton final state would come from the pair production of the light doubly charged Higgs boson present in the model. The presence of such doubly charged Higgs bosons has been sought by experimentalists in the context of various other models at the Tevatron as well as the LHC [22], which put strong limits on the masses of such particles.

In Fig. 2 we plot the production cross sections for the pair production of doubly charged Higgsinos (both chirality) as well as for the right-handed doubly charged Higgs boson. Note that the production cross section for the left-handed doubly charged Higgsino is much larger than

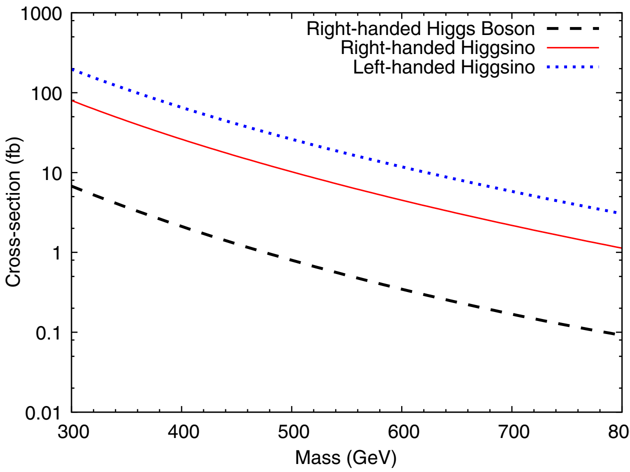

FIG. 2 (color online). Production cross sections for $\tilde{\delta}_{L,R}^{\pm\pm}$ pair and $\delta_R^{\pm\pm}$ at the LHC at 14 TeV.

the right-handed one. This is due to the bigger Z boson coupling with the left-handed doubly charged Higgsino. However for larger values of the mass, the required center-of-mass energy to produce the particles in pair also increases and therefore an s-channel suppression would appear in the case of the left-handed doubly charged Higgsino as the center-of-mass energy moves away from the Z boson pole mass, i.e. $\frac{1}{\hat{s}-M_Z^2} \longrightarrow \frac{1}{\hat{s}}(\hat{s} \gg M_Z^2)$. In comparison the Z_R contribution would increase as the center-of-mass energy starts approaching the Z_R boson pole mass, i.e. $\frac{1}{\hat{s}} \longrightarrow \frac{1}{\hat{s}-M_{Z_R}^2}(\hat{s} \sim M_{Z_R}^2)$ which also has larger coupling to the right-handed doubly charged Higgsino. This effect is visible for very large values of the Higgsino mass (although not shown in the Fig. 2) where we find that the production cross section for the left-handed Higgsino actually falls below the production cross section of the right-handed Higgsino. It can also be seen that the Higgsino production cross sections are much larger than the doubly charged Higgs boson production rate (for the same mass) and hence they effectively help in enhancing the 4-lepton signal at colliders. In general, from spin arguments we might expect the production cross section of the fermion to be four times that of the scalar, but this is only true in the massless limit. One can think that since the center-of-mass energy is much higher than the masses of the particles the massless limit should be a good approximation, but turning on the parton distribution function produces partons of all energies and hence we get a cross-section ratio which is much higher. The Higgsino process also gives a unique signal with $4\ell + \not{E}_T$, which is not present for the doubly charged Higgs boson pair-production process.

Considering the decays of the doubly charged particles discussed before, we find that the final states coming from the pair production and subsequent decays of the doubly charged Higgsinos are two pairs of same-sign leptons of same or different flavor (i.e., e or μ) and missing energy. We want to focus on all the possibilities with the final states consisting of same flavor or different flavor leptons, with and without missing energy.

As we have no hint of SUSY signals yet at the LHC, it can be safely assumed that the SUSY particles are heavy and difficult to produce at the current energies at which LHC was run. We therefore restrict ourselves to the low lying mass spectrum of some of the SUSY particles and their decay probabilities to study its signals. Since the model in study naturally accommodates light doubly charged particles, we assume all other SUSY partners as well as the Higgs scalars to be much heavier than the doubly charged Higgsinos and the doubly charged Higgs boson (from the right-handed sector). The only other particle which is assumed to be lighter is the lightest neutralino, which is the LSP. With this choice of the spectrum, the decay patterns for the doubly charged particles are known and have already been discussed earlier. To highlight the signal, we have considered the following two representative points:

(i) For the first choice, which we call *BP1* (Benchmark Point 1), we consider a doubly charged Higgs boson with mass 300 GeV, an LSP neutralino with a mass of 80 GeV, charged sleptons with mass of 1 TeV and doubly charged Higgsinos with a mass of 500 GeV. With this choice we focus our attention on two particular scenarios. First, we analyze the situation where all the finals state leptons coming from the decay are of the same flavor (e.g. all the final state leptons are either electrons or muons) while the other case is when each doubly charged particle decays to a different flavor pair (e.g. two same sign electrons and two same sign muons).

(ii) For the second choice, which we call *BP2*, we consider a lower value for the mass of the doubly charged Higgsino at 400 GeV, while the other mass choices remain the same. Note that this choice gives a larger production rate for the doubly charged Higgsinos, but also affects the kinematics of the final state decay products because of smaller mass splitting between the doubly charged Higgsino and the doubly charged Higgs boson.

In our analysis, for the charged lepton final states we have considered the signal consisting of either electrons or muons only and neglected the tau lepton. Nevertheless the decay of the doubly charged Higgs boson to tau lepton pair will be very similar to the decay into muons and electrons and is only considered less relevant due to the limited tau-tagging efficiency at experiments. However, the signal will also be dictated by the decay probabilities of the doubly charged scalar into the charged lepton pairs, and in models where the Yukawa structure demands that the decays are maximally to a pair of same-sign taus, then one needs to consider the tau final states.

We now turn our focus to analyzing the final state signal consisting of the four charged leptons with or without missing transverse energy. Note that when we do not demand any criterion for the missing transverse momenta in the final state, our signal contributions come from three different sources, i.e. pair production of the doubly charged Higgsinos (both chirality) as well as the pair production of the doubly charged scalars. This would not only enhance the four-lepton signal when compared to individual contributions but also help in identifying the nature of additional contributions to such multilepton final states. To study the signal we demand that the final state particles satisfy the following kinematic cuts:

(i) Each charged lepton must carry a minimum transverse momentum given by $p_T > 15$ GeV.

(ii) The charged leptons must lie in the central rapidity region of $|\eta_\ell| < 2.5$.

(iii) For proper resolution to detect the final state particles we set $\Delta R_{\ell\ell} > 0.2$ between the final state charged leptons, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ defines the resolution of a pair of particles in the (η, ϕ) plane.

(iv) We also specify an invariant mass cut between the opposite sign same flavor leptons such that $M_{\ell^+\ell^-} > 10$ GeV and a further cut of 80 GeV $> M_{\ell^+\ell^-} > 100$ GeV, where the latter one is aimed at removing the SM contributions coming from resonant Z boson decays.

With the above set of kinematic selections we perform a detailed numerical analysis of the final state events of the multilepton signal as well as the SM background. For our numerical analysis, we have included the model description into the event generator CALCHEP [23] and generated the event files for the production and decays of the doubly charged Higgsinos. These event files were then passed through the CALCHEP+PYTHIA [24] interface, where we include the effects of both initial and final state radiations using PYTHIA switches to smear the final states. We have used the leading-order CTEQ6L [25] parton distribution functions (PDF) for our analysis.

So there are three major processes that contribute to our signal.

(i) The direct pair production of the right-handed doubly charged Higgs bosons. Each Higgs boson then decays into a pair of same sign leptons producing a final state signal of 4 leptons. We call this ($\mathcal{C}1$),

$$pp \to \delta_R^{++}\delta_R^{--} \to \ell_i^+\ell_i^+\ell_j^-\ell_j^-.$$

(ii) Pair production of right-handed doubly-charged Higgsino. Each Higgsino decays into a right-handed doubly-charged Higgs boson and a neutralino. The doubly-charged Higgs boson then decays into a pair of same-sign leptons giving a final state signal of 4 leptons and $\not{E}_T$. We call this ($\mathcal{C}2$),

$$\begin{aligned} pp &\to \tilde{\delta}_R^{++}\tilde{\delta}_R^{--} \to \delta_R^{++}\delta_R^{--}\tilde{\chi}_1^0\tilde{\chi}_1^0 \\ &\to \ell_i^+\ell_i^+\ell_j^-\ell_j^-\not{E}_T. \end{aligned}$$

(iii) Pair production of left-handed doubly-charged Higgsino. The Higgsino decays through an off-shell slepton to a same sign lepton pair and a neutralino.[6] This process also gives a final state signal with 4 leptons and $\not{E}_T$. We call this ($\mathcal{C}3$),

$$\begin{aligned} pp &\to \tilde{\delta}_L^{++}\tilde{\delta}_L^{--} \to (\tilde{\ell}_i^{*+}\ell_i^+)(\tilde{\ell}_j^{*-}\ell_j^-) \\ &\to \ell_i^+\ell_i^+\ell_j^-\ell_j^-\tilde{\chi}_1^0\tilde{\chi}_1^0. \end{aligned}$$

All the three subprocesses mentioned above lead to a signal with four charged leptons in the final state, which is a very clean signal at a hadron machine such as the LHC, with very little SM background, and therefore should be an interesting test for the model. Significantly, one should note that the signal described by ($\mathcal{C}1$) is an important channel for the search of doubly charged particle resonances, such as double charged scalars [22] or bileptons [26], and can appear even in R-parity-violating supersymmetric models [27]. The highlight of course is that there is no source for missing transverse momenta in the signal. However, the other two signals described by ($\mathcal{C}2$) and ($\mathcal{C}3$) not only lead to four charged leptons in the final states but is also accompanied by large missing transverse momenta due to the LSP present in the final state. There could be numerous new physics scenarios where such a signal can be common and so it would be interesting to be able to identify the signal associated with our model in a unique way. We find that our signal can in general be classified into two types, one where we only demand four charged leptons in the final state and do not put any requirement on the missing transverse momenta. The other type would be to demand a minimum missing transverse momenta in the final state in addition to the four tagged charged leptons. We list the cross sections for the three subprocesses ($\mathcal{C}1$–$\mathcal{C}3$) at different LHC energies in Table I which gives the cross section for a final state consisting of same-sign pairs and all four of same-flavor (SF) charged leptons in our model for *BP1* where the doubly-charged Higgsino mass is taken as 500 GeV, doubly charged Higgs boson mass of 300 GeV, slepton mass of 1 TeV and a neutralino mass of 80 GeV. Note that the signal cross sections are invariably larger for the ($\mathcal{C}3$) as it comes from the pair production of the left-handed doubly charged Higgsinos which has the greater production rate. We can see that without any missing E_T requirement on the final state, a somewhat lower cross section for the signal coming from the pair production of doubly charged scalar is found to be enhanced considerably by including contributions from the pair production of the doubly charged Higgsinos. This enhances the sensitivity of the experiment to exotic doubly charged particles through the four charged lepton final state. With a minimum missing E_T requirement of 100 GeV on the events, it is found that the signal coming from the pair production of the doubly charged scalars is reduced drastically while the events from the pair production of the doubly charged Higgsinos are not affected much. This is expected because the doubly charged Higgsinos decay to final states consisting of the undetected LSP which carries off substantial missing energy and therefore satisfies the large $\not{E}_T$ cutoff. In Table II we show the cross section for a final state consisting of same-sign pairs where each pair is of different-flavor (DF) leptons for *BP1*. Here we assume that one of the doubly charged particle decays to one particular flavor of the charged leptons while the other decays to a different flavor. So the final states would have four charged leptons of the type $e^\pm e^\pm \mu^\mp \mu^\mp$. Note that such a combination of final state would have practically no SM background as it requires at least four W bosons to give such a combination

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[6] We assume here that the left-handed doubly charged Higgsino decays via the off-shell slepton with 100% branching probability assuming a Yukawa coupling large enough to completely dominate all other possible decay channels (cascades) of the left-handed doubly charged Higgsino.

TABLE I. Cross-section table for a final state of $\ell_i^+\ell_i^+\ell_i^-\ell_i^- + X$ with $M_{\tilde{\delta}^{\pm\pm}_{L,R}} = 500$ GeV, $M_{\delta^{\pm\pm}_R} = 300$ GeV, $M_{\tilde{\chi}^0_1} = 80$ GeV and $M_{\tilde{l}^\pm} = 1$ TeV.

	$\mathcal{C}1$		$\mathcal{C}2$		$\mathcal{C}3$	
	$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)	
LHC Energy	>0	>100	>0	>100	>0	>100
7 TeV	0.266 fb	0.033 fb	0.275 fb	0.226 fb	0.642 fb	0.568 fb
8 TeV	0.368 fb	0.048 fb	0.430 fb	0.359 fb	0.992 fb	0.927 fb
14 TeV	1.153 fb	0.228 fb	1.859 fb	1.649 fb	4.208 fb	3.667 fb

of charged leptons in the final state. The SM background coming from $W^+W^-W^+W^-$ production at LHC is too suppressed at LHC energies. For example at 8 TeV center-of-mass energy at the LHC, this cross section comes out to be less than 0.2 fb. For each of the W's to further decay in to the leptonic ($e\nu_e \& \mu\nu_\mu$) channel (with a combined branching fraction of $\sim$22%) makes them completely negligible when compared to the signal and is therefore not considered in the analysis. We neglect the τ lepton as discussed before. The cross sections are slightly greater than those listed in Table I because we have removed the additional kinematic cut on the invariant mass on the opposite-sign same flavor leptons given by 80 GeV $> M_{\ell^+\ell^-} >$ 100 GeV. As our estimates rely on the assumption that the branching fractions for the doubly charged particles decay to each flavor of charged lepton is $1/3$, we must point out that this final state will be relevant only when the decay rates to either $e^\pm e^\pm$ or $\mu^\pm\mu^\pm$ are not too suppressed.

We now consider a case where the doubly charged Higgsinos are slightly lighter (400 GeV) while the other particles have the same mass as before (*BP2*). This choice enhances the production rates for the doubly charged Higgsinos but also gives a compressed spectrum for its decays. Note that a bigger mass difference between the parent particle and its decay products would lead to greater energy for the decay products. In this case, one expects that as the LSP mass and the doubly charged Higgs mass add up very close to the doubly charged Higgsino mass, the missing transverse momenta in the events due to the LSP will be less compared to the previous case. This can be seen in Fig. 3 where we show the distribution for the differential cross section as a function of the missing transverse energy. In Fig. 3(a) we show the $\not{E}_T$ distribution in the signal events coming from the contributions of the right-handed doubly charged Higgsino and Higgs while Fig. 3(b) shows $\not{E}_T$ distribution for contributions from both the right-handed and left-handed doubly charged Higgsino including the doubly charged Higgs boson. We see that differential cross section in Fig. 3(a) has a higher fraction of events at very small $\not{E}_T$. This is because of the contribution from the direct pair production of the doubly charged Higgs boson which will have very little missing energy which might originate due to mismeasurements of the final state particles, as there is no other source of missing energy in the form of the neutralino in the final state. In Fig. 3(b) this effect is washed away because the number of events from the left handed doubly charged Higgsino pair production is now much larger compared to both the doubly charged Higgs boson and Higgsino pair production and hence their contribution is suppressed.

In Table III we give the cross sections for a final state consisting of the same-flavored charged leptons for *BP2.* Note that we have a slightly weaker requirement on the missing transverse energy of 20 GeV for the events corresponding to *BP2.* This is to avoid large suppression of the signal which can happen due to the smaller mass splittings.

In Table IV we give the cross sections for a final state consisting of different-flavored charged lepton pairs for *BP2.* Again the kinematic characteristics for the events remain the same as before but the cross section is slightly greater than that for SF events because of the removal of the kinematic cut corresponding to the invariant mass removing the Z peak for opposite sign same flavor charged lepton pairs.

We must point out here that the corresponding SM background for the four charged lepton final state with our selection cuts on the kinematic variables is found to be completely negligible and therefore has not been shown

TABLE II. Cross-section table for a final state of $\ell_i^+\ell_i^+\ell_j^-\ell_j^- + X$ with $M_{\tilde{\delta}^{\pm\pm}_{L,R}} = 500$ GeV, $M_{\delta^{\pm\pm}_R} = 300$ GeV, $M_{\tilde{\chi}^0_1} = 80$ GeV and $M_{\tilde{l}^\pm} = 1$ TeV.

	$\mathcal{C}1$		$\mathcal{C}2$		$\mathcal{C}3$	
	$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)	
LHC Energy	>0	>100	>0	>100	>0	>100
7 TeV	0.302 fb	0.032 fb	0.314 fb	0.257 fb	0.753 fb	0.672 fb
8 TeV	0.418 fb	0.047 fb	0.480 fb	0.402 fb	1.152 fb	1.078 fb
14 TeV	1.266 fb	0.216 fb	1.989 fb	1.749 fb	4.655 fb	4.051 fb

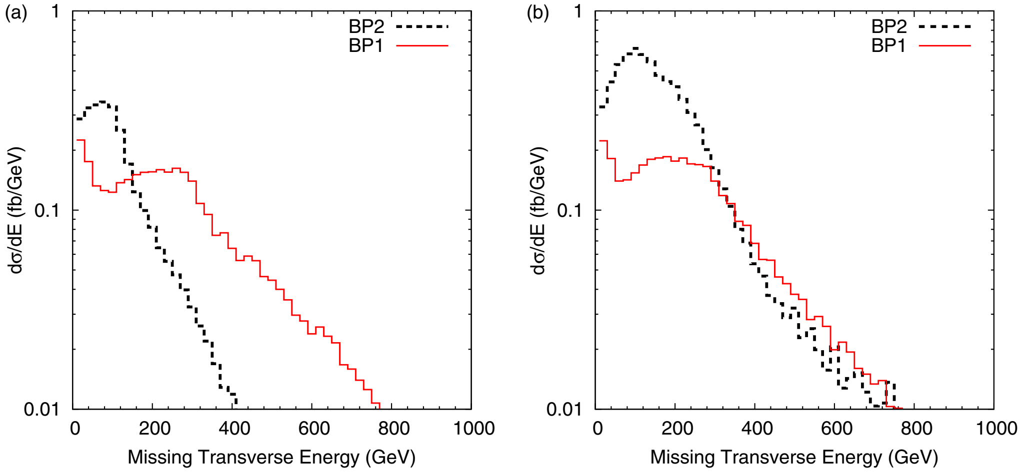

FIG. 3 (color online). (a) $\not{E}_T$ for doubly charged right-handed Higgsino and Higgs boson, (b) $\not{E}_T$ for doubly charged right-handed and left-handed Higgsinos and right-handed Higgs boson.

or considered in our analysis. The most dominant background which one expects for the SF charged lepton signal will be from the pair production of Z bosons which we have suppressed using the invariant mass cut on the opposite-sign same flavor lepton pairs. However, as we have a light doubly charged Higgs in the spectrum, we expect to see a resonance in the invariant mass distributions of like-signed charge lepton pairs. We have already shown that there are three different subprocesses for the signal contributions for the $4\ell + X$ final state and the cross section for ($\mathcal{C}3$) is much larger than ($\mathcal{C}1$) and ($\mathcal{C}2$). Note that ($\mathcal{C}3$) corresponds to the signal where the left-handed doubly charged Higgsino is pair produced and decays through an off-shell slepton. Therefore one does not expect any resonance behavior in the invariant mass distributions of the charged lepton pairs but a kinematic edge is expected [20]. This would mean that a part of the signal itself acts as a background to smear out the resonant signal for the doubly charged Higgs boson. This is in fact the highlight of our analysis where we show that our signal actually stands out as a resonance and is also enhanced because of the additional contributions coming from the heavy doubly charged fermion production.

To show some kinematic characteristics of the events for the SF signal we take the case of $e^+e^+e^-e^-$ in the final state and for the DF signal we take $\mu^-\mu^-e^+e^+$. We put the aforementioned cuts and simulate the events using CalcHEP and Pythia and look at the ΔR_{ll} and invariant mass M_{ll} of the final state leptons.

The ΔR_{ll} for the same-sign and opposite-sign final state charged leptons of same flavor for *BP1* are shown in Fig. 4. Figure 4(a) includes only the contribution of the right-handed doubly charged Higgsino and Higgs ($\mathcal{C}1 + \mathcal{C}2$), while Fig. 4(b) denotes the contribution from the doubly charged Higgs as well as both the right-handed and left-handed doubly charged Higgsino ($\mathcal{C}1 + \mathcal{C}2 + \mathcal{C}3$). It is worth noting that in each plot there is a marked difference between the same-sign lepton and the opposite-sign leptonic final states. It can be seen that for the same-sign charged leptons the distribution is peaked at low values of ΔR while the opposite-sign charged leptons have a ΔR which is peaked at a much higher value. This is what is expected since the same-sign pair of leptons arise from the decay of a single doubly charged Higgs boson while the opposite-sign leptons arise from two different particles and hence are much further apart. The measurement of ΔR at the LHC for a four-lepton final state can thus give a definite indication of the existence of a doubly charged particle if the distribution is similar to what we get in our analysis. Note that the ΔR distributions are also very sensitive to the boost of the mother particle as larger boost will make the decay products come out more closer to each other.

TABLE III. Cross-section table for a final state of $\ell_i^+\ell_i^+\ell_i^-\ell_i^- + X$ with $M_{\tilde{\delta}^{\pm\pm}_{L,R}} = 400$ GeV, $M_{\delta^{\pm\pm}_R} = 300$ GeV, $M_{\tilde{\chi}^0_1} = 80$ GeV and $M_{\tilde{l}^\pm} = 1$ TeV.

	$\mathcal{C}1$		$\mathcal{C}2$		$\mathcal{C}3$	
	$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)	
LHC Energy	>0	>20	>0	>20	>0	>20
7 TeV	0.266 fb	0.143 fb	0.871 fb	0.823 fb	1.797 fb	1.774 fb
8 TeV	0.368 fb	0.203 fb	1.248 fb	1.183 fb	2.576 fb	2.550 fb
14 TeV	1.153 fb	0.737 fb	4.467 fb	4.309 fb	8.892 fb	8.806 fb

TABLE IV. Cross-section table for a final state of $\ell_i^+\ell_i^+\ell_j^-\ell_j^- + X$ with $M_{\tilde{\delta}^{\pm\pm}_{L,R}} = 400$ GeV, $M_{\delta^{\pm\pm}_R} = 300$ GeV, $M_{\tilde{\chi}_1^0} = 80$ GeV and $M_{\tilde{l}^\pm} = 1$ TeV.

	$\mathcal{C}1$		$\mathcal{C}2$		$\mathcal{C}3$	
	$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)		$\not{E}_T$ (GeV)	
LHC Energy	>0	>20	>0	>20	>0	>20
7 TeV	0.302 fb	0.149 fb	1.009 fb	0.949 fb	2.332 fb	2.308 fb
8 TeV	0.418 fb	0.213 fb	1.451 fb	1.358 fb	3.327 fb	3.288 fb
14 TeV	1.266 fb	0.721 fb	4.804 fb	4.610 fb	10.886 fb	10.767 fb

In Fig. 5 we show the invariant mass distributions for the same-sign and opposite-sign final state leptons of same flavor for *BP1*. Note that for the opposite-sign lepton pair invariant mass there are no events between 80 and 100 GeV. This is due to the cut that we applied to get rid of the Z peak for the SM background. The invariant mass for the opposite-sign leptons do not show any resonant behavior. For the same-sign lepton pairs, we see a pronounced peak at an invariant mass of 300 GeV which is the doubly charged Higgs boson mass. As we include the contributions coming from the pair production of the left-handed doubly charged Higgsino, the resonant peak is seen to broaden a little but is still very significant. Such a peak, though very difficult to see without *a priori* knowledge of the Higgs boson mass, would be a definite proof of a doubly charged particle if seen in the detector. It is also worth noting the distinct kinematic edge seen in the invariant mass distribution of the like-sign charged lepton pair in both Figs. 5(a) and 5(b). The edge in Fig. 5(a) is at a different M_{ll} when compared to that in Fig. 5(b). Note that in Fig. 5(a) the resonant peak is because of the doubly charged Higgs decaying to two same-sign leptons while the sharp cutoff in the distribution is because of the maximum invariant mass allowed for the lepton pair that comes from $\delta_R^{\pm\pm} \to \ell^\pm\ell^\pm$. This would mean that the distribution will fall rapidly beyond the resonance which is the $\delta_R^{\pm\pm}$ mass. On the other hand, the signal in Fig. 5(b) is completely dominated by the contributions coming from the left-handed doubly charged Higgsino production and therefore it washes away the kinematic edge from the other subprocesses. The sharp cutoff in Fig. 5(b) then appears because of $\tilde{\delta}_L^\pm \to (\tilde{\ell}_i^{*\pm}\ell_i^\pm) \to \ell_i^\pm\ell_i^\pm\tilde{\chi}_1^0$ and is given by (in the rest frame of the decaying particle) $M^{\max}_{l^\pm l^\pm} = \sqrt{M^2_{\tilde{\delta}_L^{\pm\pm}} + M^2_{\tilde{\chi}_1^0} - 2M_{\tilde{\delta}_L^{\pm\pm}}E_{\tilde{\chi}_1^0}}$, where $E_{\tilde{\chi}_1^0}$ is the energy of the LSP. This yields an edge in the invariant mass distribution of the same-sign same flavor charged lepton pairs at the bin around $M_{l^\pm l^\pm} = M_{\tilde{\delta}_L^{\pm\pm}} - M_{\tilde{\chi}_1^0} \simeq 420$ GeV. It is interesting to observe that we find a distinct resonance in the invariant mass distribution as well as a sharp kinematic edge due to the off-shell decay of the left-handed doubly charged Higgsino which clearly highlights an additional contribution to the resonant signal of doubly charged scalar production leading to four charged lepton final states.

We can also consider the case where the right-handed doubly charged Higgsino too decays via off-shell doubly charged scalar which can be realized when the right-handed doubly charged Higgsino is not much heavier than the right-handed doubly charged Higgs boson such

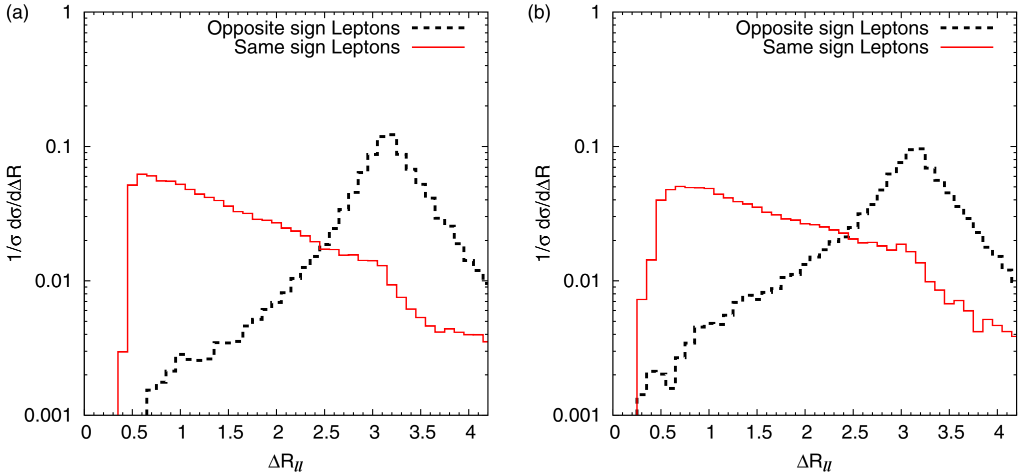

FIG. 4 (color online). (a) Illustrating the ΔR_{ll} distribution for events coming from the doubly charged right-handed Higgsino and Higgs boson pair production and (b) ΔR_{ll} distribution for events when the contributions from the pair production of the left-handed Higgsinos is also included for *BP1*.

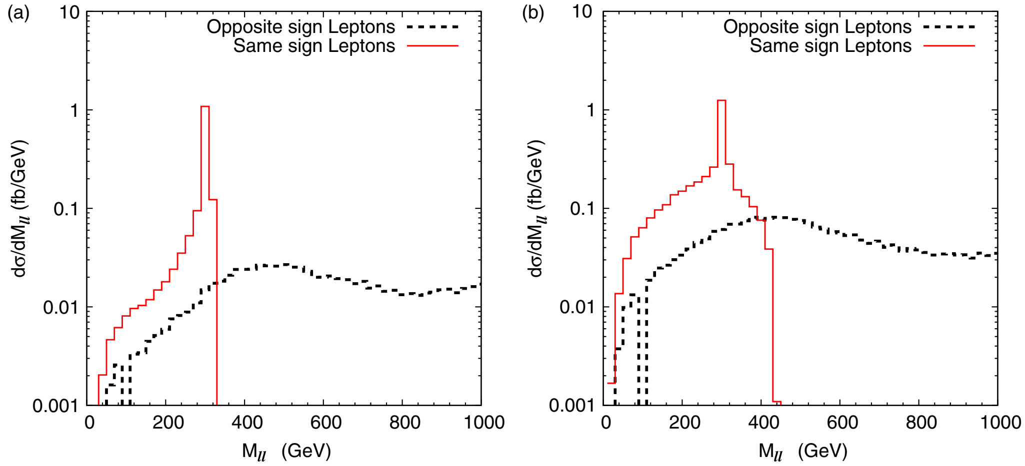

FIG. 5 (color online). Illustrating the (a) invariant mass distribution for events coming from the doubly charged right-handed Higgsino and Higgs boson pair production and, (b) invariant mass distribution for events when the contributions from the pair production of the left-handed Higgsinos is also included for *BP1*.

that $M_{\tilde{\delta}_R^{\pm\pm}} < M_{\delta_R^{\pm\pm}} + M_{\tilde{\chi}_1^0}$. In this case the Higgsino will decay into the LSP and two same sign leptons through an off-shell doubly charged Higgs boson. In Fig. 6 we show the invariant mass distribution for the charged lepton pairs, where the doubly charged Higgsino mass is 350 GeV, the doubly charged Higgs boson mass is 300 GeV and the LSP mass is 80 GeV. We see that in such a case the resonant peak in the same-sign charged lepton pair is lost but a kinematic edge exists at around 270 GeV. Note that we still expect a narrow resonance from the direct pair production of the doubly charged scalar and an enhanced signal rate but we do not see any new enhancement at the resonance.

Experiments at the LHC are looking for doubly charged Higgs bosons by analyzing final states with four high p_T charged leptons. Our model gives a resonant multilepton signal with large missing energy depending on the mass difference between the doubly charged Higgs boson and the Higgsino. Such a signal accompanied by a peak in the same-sign lepton invariant mass distribution of the same-sign charged lepton pair. This will clearly suggest an alternative signal not restricted to the direct production of doubly charged scalars. This can definitely be a possible channel for the discovery of the doubly charged Higgsinos which might be worth looking for.

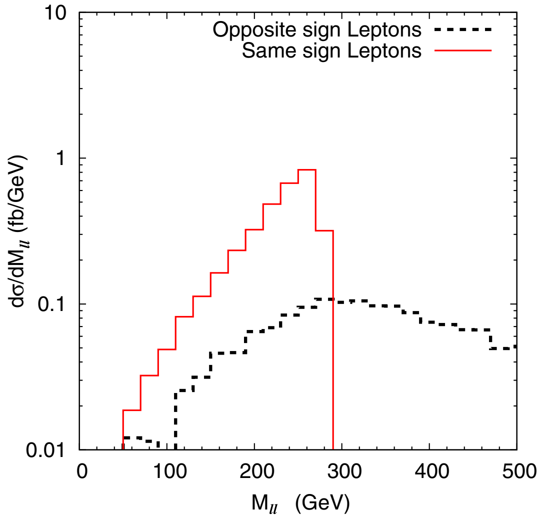

FIG. 6 (color online). Invariant mass distribution in M_{ll} for a doubly charged right-handed Higgsino which decays through an off-shell doubly charged Higgs boson.

IV. DISCUSSION AND CONCLUSION

In this work we have studied the pair production and decay of the doubly charged Higgsinos in the left-right supersymmetric model and looked at the possible collider signatures at the LHC. The four-lepton-plus-missing-energy signal has a variety of distinct features that can easily distinguish it from other signals, arising especially from the minimal supersymmetric standard model.

We have studied the multilepton final state $2\ell^+ 2\ell^- + \not{E}_T$ arising in the left-right SUSY model. We find that there are three distinct subprocesses that contribute to the signal. We have shown through two representative points in the model how each subprocess dominates the signal depending on the kinematic requirements on the missing transverse momenta. We also show through various kinematic distributions the highlight of the four-lepton signal in this model. Using specific cuts on the final states, we find that there is very little background from SM. The major background at the LHC where two Z bosons decay into four charged leptons is minimized by putting an invariant mass cut which neglects events at the Z boson peak. Thus, the signal produced by our model at the colliders would be clean and very easy to distinguish from other competing models. Large missing transverse momenta in the final state can be triggered to rule out contributions coming from the direct production of doubly charged scalars and therefore would give a strong hint of a supersymmetric model with doubly charged particles. The data collected by the LHC experiments should already provide significant constraints on the masses of the doubly charged Higgsino and Higgs boson through the process outlined here. Dedicated searches for these doubly charged particles in the channel proposed here by the experimental collaborations will be highly desirable.

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APPENDIX

In this Appendix we list all the Feynman rules necessary for analyzing productions and decays of doubly charged Higgsinos in the LRSUSY model.

Fermion-Fermion-Z Boson, γ:

(i) $\gamma^\mu \tilde{\delta}_{L,R}^{--} \bar{\tilde{\delta}}_{L,R}^{--}$: $2ie\gamma^\mu$

(ii) $Z_L^\mu \tilde{\delta}_L^{--} \bar{\tilde{\delta}}_L^{--}$: $i\frac{g_L \cos 2\theta_W}{\cos\theta_W}\gamma^\mu$

(iii) $Z_L^\mu \tilde{\delta}_R^{--} \bar{\tilde{\delta}}_R^{--}$: $-i\frac{2g_L \sin^2\theta_W}{\cos\theta_W}\gamma^\mu$

(iv) $Z_R^\mu \tilde{\delta}_L^{--} \bar{\tilde{\delta}}_L^{--}$: $-i\frac{g_L \sin^2\theta_W}{\sqrt{\cos 2\theta_W}\cos\theta_W}\gamma^\mu$

(v) $Z_R^\mu \tilde{\delta}_R^{--} \bar{\tilde{\delta}}_R^{--}$: $i\frac{g_L(1-3\sin^2\theta_W)}{\cos\theta_W\sqrt{\cos 2\theta_W}}\gamma^\mu$

(vi) $Z_R^\mu u\bar{u}$: $i\frac{g_L(3-8\sin^2\theta_W+3\gamma_5\cos 2\theta_W)}{12\cos\theta_W\sqrt{\cos 2\theta_W}}\gamma^\mu$

(vii) $Z_R^\mu d\bar{d}$: $-i\frac{g_L(3-4\sin^2\theta_W+3\gamma_5\cos 2\theta_W)}{12\cos\theta_W\sqrt{\cos 2\theta_W}}\gamma^\mu$.

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