Doubly charged Higgs from $e$-$\gamma$ scattering in the 3-3-1 Model

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Abstract

We studied the production and signatures of doubly charged Higgs bosons in the process $\gamma e^- \rightarrow H^- E^+$, where $E^+$ is a heavy lepton, at the $e^- e^+$ International Linear Collider (ILC) and CERN Linear Collider (CLIC). The intermediate photons are given by the Weizsäcker-Williams and laser backscattering distributions. We found that significant signatures are obtained by bremsstrahlung and backward Compton scattering of laser. A clear signal can be obtained for doubly charged Higgs bosons, doubly charged gauge bosons and heavy leptons.

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I. INTRODUCTION

Nowadays it is well established that the Standard Model (SM) of electroweak interactions describes very well almost every subatomic phenomenon up to order of $\approx 100 \text{ GeV}$ \cite{1}. However, there is a lot of experimental results that are not well understood or nor embedded in their predictions. Among the many attempts to generalize the SM, several of them involve extensions of the Higgs sector. After spontaneous symmetry breaking, those extensions that add scalar triplet to the Higgs sector and left-right symmetry models end up with physical doubly charged Higgs bosons (DCHBs) in its particle spectrum \cite{2}. The DCHBs ($H^{\pm\pm}$) have some interesting consequences. The main one is related to the seesaw mechanism, which is capable of generating a small mass for the neutrino. These models are manifested in the higher energy range and the scheme is constructed so that the neutrino mass is inversely proportional to this new energy scale. This relationship can provide an idea of why the neutrino mass is so small compared with Fermi scale \cite{3}. One of the major motivations for the study of these particles with double charge comes from the fact that experimental physicists expect to find this kind of particles at the Large Hadron Collider (LHC), ILC and CLIC.

The Fermilab Tevatron can detect DCHBs via pair production if its mass does not exceed $\approx 275 \text{ GeV}$ an at the LHC this limit rises up to $\approx 850 \text{ GeV}$. At the Tevatron, an attempt to directly detect DCHBs were carried out based on the channel $\bar{q}q \to H^{-}H^{++}$ looking for decay mode $H^{\pm\pm} \to \ell_{i}^{\mp} \ell_{j}^{\pm}$, where $\ell_{i,j}$ are known charged leptons. Four-lepton final states was observed by D0 Collaboration \cite{4}, while in CDF was observed $e^{+}e^{+}e^{-}e^{-}$, $\mu^{+}\mu^{+}\mu^{-}\mu^{-}$ and states involving $\tau$ leptons \cite{5}. These searches were done for left-right Model. Then, assuming a $\text{BR}(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 50\%$, left (right) chiral DCHBs with masses larger than 150 (136) GeV and 127 (113) GeV, respectively, are excluded \cite{1}.

In this paper we work under the 3-3-1 electroweak model \cite{6-8}. In this class of models the electroweak symmetry gauge group $SU(2)_{L} \otimes U(1)$ of the SM is extended to $SU(3)_{L} \otimes U(1)_{N}$. The simplest version of scalar sector of the model has only three Higgs triplets \cite{8}. Consequently, this model predicts the existence of eight physical Higgs bosons which are four neutral bosons $h^{0}$, $H_{1}^{0}$, $H_{2}^{0}$ and $H_{3}^{0}$, a pair of single charged bosons $H^{\pm}$, and a pair of DCHBs. It loses the perturbative character on a scale of a few TeV, so that, we can admit that this is the upper limit of energy for the model under consideration \cite{9}. This class of models is
one of the most interesting alternatives to the SM. The process of cancellation of anomalies requires that the number of families be an integer multiple of the number of colors. But, since QCD requires that the number of colors is less than five, then in the 3-3-1 model the number of families is exactly three.

We are interested in production of single DCHB via interactions $\gamma e^-$ from $e^+e^-$ collisions in International Linear Collider (ILC) and in CERN Linear Collider (CLIC). The version of the 3-3-1 model which we studied predicts the existence of heavy leptons $P_{\ell a}$ ($P_{\ell a} = E, M, T$). Hence, the process to be consider is $e^-\gamma \to H^-E^+$, which receives contributions of $H^-$ and $U^-$ exchange in the $t$ channel and $e$ in the $s$ channel.

In the next Section we will present the main features of the version of the 3-3-1 Model under consideration. In Sec. III we will give the expressions for production cross sections and finally, in Sec. IV we will describe the results and conclusions.

II. OVERVIEW OF THE MODEL

We will summarize in this section only the most relevant points of the model. For details see Ref. The left-handed leptons and quarks transform under the SU(3)$_L$ gauge group as the triplets

$$\psi_{aL} = \begin{pmatrix} \nu_{\ell a} \\ \ell'_a \\ P'_{\ell a} \end{pmatrix}_L \sim (3, 0) \quad Q_{1L} = \begin{pmatrix} u'_1 \\ d'_1 \\ J_1 \end{pmatrix}_L \sim \left(3, \frac{2}{3}\right),$$

$$Q_{\alpha L} = \begin{pmatrix} J'_\alpha \\ u'_{\alpha} \\ d'_{\alpha} \end{pmatrix}_L \sim \left(3^*, -\frac{1}{3}\right),$$

where $\ell'_a = e', \mu', \tau'$ and $\alpha = 2, 3$. The $J_1$ exotic quark carries $5/3$ units of elementary electric charge, while $J_2$ and $J_3$ carry $-4/3$ each one. In Eqs. the numbers $0, 2/3$, and $-1/3$ are the U(1)$_N$ charges. Each left-handed charged fermion has its right-handed counterpart transforming as a singlet in the presence of the SU(3)$_L$ group, i.e.,

$$\ell'_{aR} \sim (1, -1) \quad P'_{\ell aR} \sim (1, 1) \quad U'_{aR} \sim (1, 2/3),$$
\[ D'_R \sim (1, -1/3), \quad J_{1R} \sim (1, 5/3) \quad J'_{\alpha} \sim (1, -4/3). \] 

We are defining \( U = u, c, t \) and \( D = d, s, b \). It should be noted that, in order to avoid anomalies, one of the quark families must transform in a different way with respect to the others. In Eqs. (1) all the primed fields are linear combinations of the mass eigenstates. The charge operator is defined by

\[ \frac{Q}{e} = \frac{1}{2} \left( \lambda_3 - \sqrt{3} \lambda_8 \right) + N, \]  

where \( \lambda_3 \) and \( \lambda_8 \) are the diagonal Gell-Mann matrices. We notice, however, that since \( Q_{\alpha L} \) in Eqs. (1a) are in antitriplet representation of \( SU(3)_L \), the antitriplet representation of the Gell-Mann matrices must also be used in Eq. (2) in order to get the correct electric charge for the quarks of the second and third generations.

The three Higgs scalar triplets

\[
\begin{pmatrix}
\eta^0 \\
\eta^-_1 \\
\eta^+_2
\end{pmatrix} \sim (3, 0), \quad \rho = \begin{pmatrix}
\rho^+ \\
\rho^0 \\
\rho^{++}
\end{pmatrix} \sim (3, 1), \quad \chi = \begin{pmatrix}
\chi^- \\
\chi^0
\end{pmatrix} \sim (3, -1),
\] 

are the minimal content of Higgs sector enough to break the symmetry spontaneously and generate the masses of fermions and gauge bosons in the model. The neutral scalar fields develop the vacuum expectation values (VEVs) \( \langle \eta^0 \rangle = v_\eta, \langle \rho^0 \rangle = v_\rho \) and \( \langle \chi^0 \rangle = v_\chi \), with \( v_\eta^2 + v_\rho^2 = 246^2 \) GeV^2.

The pattern of symmetry breaking is \( SU(3)_L \otimes U(1)_N \xrightarrow{\langle \eta^0 \rangle} SU(2)_L \otimes U(1)_Y \xrightarrow{\langle \eta^0, \rho^0 \rangle} U(1)_{em} \) and so, we can expect

\[ v_\chi \gg v_\eta, v_\rho. \] 

Then, after the symmetry breaking, the masses of scalar fields become,

\[
\begin{align*}
m_{H^0_1}^2 &\approx 4\frac{\lambda_2 v_\rho^4}{v_\eta^2} - 2\lambda_1 v_\eta^4, & m_{H^0_2}^2 &\approx \frac{v_W^2}{2v_\eta v_\rho} v_\chi^2, & m_{H^0_3}^2 &\approx -\lambda_3 v_\chi^2, \quad (5a) \\
m_h^2 &\approx \frac{f v_\chi}{v_\eta v_\rho} \left[ v_\eta^2 + \left(\frac{v_\eta v_\rho}{v_\chi}\right)^2 \right], & m_{H^+}^2 &\approx \frac{v_W^2}{2v_\eta v_\rho} \left( f v_\chi - 2\lambda_7 v_\eta v_\rho \right), & (5b) \\
m_{H^\pm}^2 &\approx \frac{v_\eta^2 + v_\rho^2}{2v_\eta v_\chi} \left( f v_\rho - 2\lambda_8 v_\eta v_\chi \right), & m_{H^{\pm\pm}}^2 &\approx \frac{v_\rho^2 + v_\chi^2}{2v_\rho v_\chi} \left( f v_\eta - 2\lambda_9 v_\rho v_\chi \right). \quad (5c)
\end{align*}
\]
where in Eqs. (5a) we have considered Eq. (4). Due to the transformation properties of the fermion and the Higgs fields under SU(3)$_L$ [see Eqs. (1) and (3)] the Yukawa interactions in the model are

\[
\mathcal{L}_Y^\ell = -G_{ab}\bar{\psi}_{aL}\ell'_b\rho - G'_{ab}\bar{\psi}_{aL}P'_{bR}\chi + H.c.,
\]

\[
\mathcal{L}_Y^q = \sum_a \left[ G_{1a}U_{aR}\eta + \tilde{G}_{1a}D_{aR}\rho \right] + \sum_a \left[ F_{aa'\alpha}U_{aR}\eta + \tilde{F}_{aa'\alpha}D_{aR}\rho \right] + \sum_{\alpha,\beta} F_{J\alpha\beta}Q_{\alpha L}J_{\beta R}\chi + H.c.,
\]

where $G$'s, $\tilde{G}$'s, $F$'s, and $\tilde{F}$'s are Yukawa coupling constants with $a, b = 1, 2, 3$ and $\alpha, \beta = 2, 3$. The interaction eigenstates, which appear in Eqs. (6), can be transformed into the corresponding physical eigenstates by appropriated rotations, i.e.,

\[
\ell'_aL = U_{ab}\ell_bL, \quad \ell'_aR = U_{ab}\ell_bR, \quad P'_{aL} = V_{ab}P_{bL}, \quad P'_{aR} = V_{ab}P_{bR}, \quad \nu'_{aL} = U_{ab}'\nu_{bL}.
\]

However, since the cross-section calculations imply summation on flavors (Sec. III) and the rotation matrix must be unitary, the mixing parameters have no essential effects for our purpose here. So, hereafter we suppress the prime notation for the interaction eigenstates.

The Lagrangian (6a) shows that the ordinary particle masses are proportional to $v_\rho$ and $v_\eta$, while the heavy ones are proportional to $v_\chi$. We are not considering here neutrino masses since they are not important in the discussion.

The gauge bosons consist of an octet $W^i_\mu$ ($i = 1, \ldots, 8$), associated with SU(3)$_L$ and a singlet $B_\mu$ associated with U(1)$_N$. The covariant derivative is

\[
D_\mu\varphi_a = \partial_\mu\varphi_a + ig/2 (W_\mu, \lambda)^b_a \varphi_b + ig'N\varphi_a B_\mu,
\]

where $\varphi_a = \eta, \rho, \chi$. The model predicts single-charged ($V^\pm$), doubly-charged ($U^{\pm\pm}$) vector bileptons and a new neutral gauge boson ($Z'$) in addition to the charged standard gauge bosons $W^\pm$ and the neutral standard $Z$. The masses of the new gauge bosons are

\[
m^2_{Z'} \approx \left(\frac{ev_\chi}{s_W}\right)^2 \frac{2(1-s^2_W)}{3(1-4s^2_W)} \quad m^2_V = \left(\frac{e}{s_W}\right)^2 \frac{v_\eta^2 + v_\chi^2}{2} \quad m^2_U = \left(\frac{e}{s_W}\right)^2 \frac{v_\rho^2 + v_\chi^2}{2}.
\]

where $s_W = \sin\theta_W$. The charged currents are read off from
\[ \mathcal{L}_C = -\frac{g}{\sqrt{2}} \sum_a \left( \bar{\ell}_a L \gamma^\mu \nu_{\ell_a} L W^-_\mu + \bar{P}_\ell \ell_a L \gamma^\mu K_{ab} \nu_{\ell_b} L V^+_\mu + \bar{\ell}_a L \gamma^\mu K^{\dagger}_{ab} P_{\ell_b} L U^{--} \right) + \text{c.H.}, \]  

(10)

where \( K = V^{L\dagger} U^L \) is a mixing matrix.

The main motivation of this work is to show that in the context of the 3-3-1 model of Ref. [8], the signatures for DCHBs can be significant at the ILC and at the CLIC. One way to search for \( H^{\pm\pm} \) and \( E^\pm \) is through the process \( e^- \gamma \rightarrow H^{--} E^+ \), where the photons comes either from bremsstrahlung or from laser backscattering. Our results indicate a satisfactory number of events to establish the signal. Analyzing it we can make inferences about the existence of DCHBs, doubly charged gauge bosons and heavy leptons.

III. CROSS SECTION PRODUCTION

We study the direct DCHBs production in the process \( \gamma e^- \rightarrow H^{--} E^+ \), which occurs through the contribution of the \( s \) channel, as shown in Fig. 1, and the contributions of the \( H^{\pm\pm} \) and \( U^{\pm\pm} \) in the \( t \) channel (see Fig. 2). We assume the intermediate photon is produced either by the Weizsäcker-Williams [11] or by backscattering of laser from the \( e^- \) beam [12].

The interactions Lagrangian is given Sec. II and in several papers (see, for example, Ref. [13]). Then we evaluate the differential subprocess cross section for this reaction as

\[
\frac{d\hat{\sigma}}{d\cos \theta} = \frac{\beta \alpha}{8s} \left[ m_E^2 (-m_E^2 + \hat{t}^2) \frac{\Lambda^2 \Lambda E^2}{(\hat{t} - m_{H^{\pm\pm}}^2)^2} + 16 \alpha^2 \pi \Lambda^2_{U\gamma} \Lambda^2_{e\nu} \left( \frac{m_E^4}{m_U^2} \hat{t} - \frac{m_E^2}{m_U^2} \hat{t} + \frac{m_E^2}{2m_U^2} \hat{t}^2 + m_E^2 - \hat{t} \right) + \frac{\Lambda^2_{eE}}{s^2} \left( m_E^2 m_{H^{\pm\pm}}^2 - m_{H^{\pm\pm}}^2 \hat{u} + m_E^4 - m_E^2 \hat{t} - 2m_E^2 \hat{u} + \hat{u}^2 \right) \right].
\]  

(11)

It should be mention that the interference terms give not any contributions to this cross section and the \( \Lambda_i \) are given in the form

\[
\Lambda_\eta = \frac{v_\eta^2 - v_\nu^2}{v_\eta^2 + v_\nu^2}, \quad \Lambda_{eP} = \frac{i}{2} \frac{v_\eta}{v_\eta^2 + v_\nu^2} + \frac{i}{2} \frac{v_\nu}{v_\eta^2 + v_\nu^2}, \quad \Lambda_{U\gamma} = i \frac{v_\eta v_\chi}{\sin \theta_W \sqrt{2 v_\eta^2 + v_\chi^2}}, \quad \Lambda_{UeP} = -\frac{i}{2 \sqrt{2} \sin \theta_W}.
\]  

(12a, b)
α is the fine structure constant which we take equal to \( \alpha = 1/128 \), \( \sqrt{s} \) is the center of mass (cm) energy of the \( \gamma e^- \) system and the kinematic invariants are \( \hat{C} (\hat{u}) = C_- (C_+) \) with

\[
C_\mp = m_{H^{\mp \mp}}^2 - \frac{\hat{s}}{2} \left\{ 1 + \frac{m_{H^{\mp \mp}}^2 - m_E^2 \mp}{s} \right\} \cos \theta \left[ \left( 1 - \frac{m_{H^{\mp \mp}}^2 + m_E^2}{s} \right) \left( 1 - \frac{m_{H^{\mp \mp}}^2 - m_E^2}{s} \right) \right]^{1/2},
\]

where \( \theta \) is the angle between the DCHB and the incident electron in the cm-frame, in this frame \( \Lambda_{\gamma}^\mu \) is the vertex strength of the \( H^{\pm \pm} \) to \( \gamma \) and \( H^{\pm \pm} \) (\( \Lambda_{\gamma}^\mu = \Lambda_\gamma (p_1 - q_1)^\mu \)) with \( q_1 \) and \( p_1 \) being the momentum four-vectors of the \( \gamma \) and \( H^{\pm \pm} \), respectively. \( \Lambda_{eE} \) is the vertex strength of the \( H^{\pm \pm} \) to \( e^\pm \) and \( E^\pm \), \( \Lambda_{\gamma}^{\mu \nu} \) is for \( U^{\pm \pm} \) to \( \gamma \) and \( H^{\pm \pm} \) (\( \Lambda_{\gamma}^{\mu \nu} = \Lambda_\gamma g^{\mu \nu} \)), \( \Lambda_{eE} \) for \( U^{\pm \pm} \) to \( e^\pm \) and \( E^\pm \) and the others couplings are given in [13]. It is to note that in previous papers [13, 14, 16, 17], was made an error in the calculation of the coupling \( H^{\pm \pm} \rightarrow e^\pm P_a^\pm \), where the index \( a \) denotes the flavor, this error was now corrected (12a). We are assuming \( \sin^2 \theta_W = 0.2319 \) [1]. So we obtain the total cross section for this process folding \( \hat{\sigma} \) with the one photon luminosities

\[
\sigma = \int_{x_{\text{min}}}^1 dL \frac{d\sigma}{dT} (\hat{s} = xs) = \int_{x_{\text{min}}}^1 dx f_{\gamma/\ell} (x) \int \frac{d\sigma}{d\cos \theta} d\cos \theta,
\]

where \( x_{\text{min}} = (m_{H^{\pm \mp}} + m_E)^2 \).

IV. RESULTS AND CONCLUSIONS

Here we present the cross section for the process \( e^\mp \gamma \rightarrow H^{\mp \mp} E^\pm \) for the ILC (1.0 (1.5)) TeV and CLIC (3 TeV). All calculations were done according to [14, 15] and we obtain for the parameters and the VEV, the following representative values: \( \lambda_1 = -0.36 \), \( \lambda_2 = \lambda_3 = -\lambda_6 = -1 \), \( \lambda_4 = 2.98 \), \( \lambda_5 = -1.57 \), \( \lambda_7 = -2 \), \( \lambda_8 = -0.42 \), \( v_\eta = 195 \) GeV, these parameters and VEV are used to estimate the values for the particle masses which are given in Table I.

It is remarkable that the cross sections were calculated for every mass \( m_{H^{\pm \mp}} \) and for every \( \lambda_9 \) in such a way as to guarantee the approximation \( -f \simeq v_\chi \) [14, 15] (Table II and III). It must be taking into consideration that the branching ratios of \( H^{\pm \mp} \) are dependent on the parameters of the 3-3-1, which determines the size of various decay modes.
TABLE I: Values for the particle masses used in this work. All the values in this Table are given in GeV.

| $f$   | $v_\chi$ | $m_E$ | $m_M$ | $m_{T,H^0}$ | $m_{H^\pm}$ | $m_{H^-}$ | $m_V$ | $m_U$ | $m_{Z'}$ | $m_{J_1}$ | $m_{J_2,J_3}$ |
|-------|----------|-------|-------|-------------|-------------|-----------|-------|-------|---------|-----------|--------------|
| -1008.3 | 1000 | 148.9 | 875 | 2000 | 500 | 1454.6 | 0 | 183 | 467.5 | 464 | 1707.6 | 1000 | 1410 |
| -1499.7 | 1500 | 223.3 | 1312.5 | 3000 | 500 | 2164.3 | 0 | 285.2 | 694.1 | 691.7 | 2561.3 | 1500 | 2115 |

TABLE II: Values for the particle masses of $H^{\pm\pm}$ which are in accord with the relation $-f \simeq v_\chi$ and the parameter $\lambda_9$, for $v_\chi = 1000$ GeV. The values of $m_{H^{\pm\pm}}$ and $f$ are given in GeV.

| $m_{H^{\pm\pm}}$ | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $-f$            | 1004 | 1001 | 1003 | 1005 | 1008 | 997 | 1001 | 996 | 996 | 1003 | 1010 | 1002 | 995 | 1011 | 995 |
| $-\lambda_9$   | 0.67 | 0.69 | 0.74 | 0.81 | 0.9 | 1.0 | 1.13 | 1.28 | 1.44 | 1.63 | 1.84 | 2.06 | 2.30 | 2.57 | 2.84 |

The figures show the behavior of the cross section of the process $e^+e^- \rightarrow e^-\gamma \rightarrow H^-E^+X$ as a function of $m_{H^{\pm\pm}}$ for bremsstrahlung and laser backscattering photons. In that case, the cross section for the process initiated by backscattered photons is approximately up to one order of magnitude larger than the one for bremsstrahlung photons due to the distribution of backscattered photons being harder than the one for bremsstrahlung.

A. ILC Events

So in Fig. 3 and 4, we show the cross section for the ILC for bremsstrahlung distribution. Considering that the expected integrated luminosity at the ILC will be of the order of $3.8 \times 10^5$ pb$^{-1}$/yr, then the statistics give a total of $\simeq 1.8 \times 10^3 (1.0 \times 10^2) (\simeq 5.7 \times 10^3 (1.3 \times 10^3))$ events per year to produce $H^{\pm\pm}E^+$ if we take $m_{H^{\pm\pm}} = 500 \ (700)$ GeV, $v_\chi = 1000$ GeV and considering that the first two number of events ($\simeq 1.8 \times 10^3 (1.0 \times 10^2)$) correspond to 1.0 TeV and the other two ($\simeq 5.7 \times 10^3 (1.3 \times 10^3)$) to 1.5 TeV for the ILC respectively. Regarding the $v_\chi = 1500$ GeV for the same masses of $H^{\pm\pm}$ it will give a total of $\simeq 1.6 \times 10^3 (49) (\simeq 5.8 \times 10^3 (1.3 \times 10^3)$ events per year to produce the same particles, the difference between the numbers of events 49 and $1.3 \times 10^3$ is due we have calculated near the threshold for the first number of events, see Fig. 3 and 4. It is important to remark that at the ILC with the c.m. energy $\sqrt{s} = 0.5$ TeV and for the parameters chosen above we have the acceptable masses.
TABLE III: The same as Table II only instead of $v_\chi = 1000 \text{ GeV}$, we take $v_\chi = 1500 \text{ GeV}$.

| $m_{H^{\pm \pm}}$ | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 | 1700 | 1800 |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $-f$             | 1502| 1505| 1506| 1499| 1499| 1503| 1496| 1499| 1494| 1491| 1491| 1502| 1499| 1498| 1509| 1496| 1509| 1509 |
| $-\lambda_9$    | 0.66| 0.67| 0.69| 0.72| 0.76| 0.81| 0.87| 0.93| 1.01| 1.09 | 1.18 | 1.39 | 1.51 | 1.64 | 1.78 | 1.92 | 2.08 |

up to approximately $m_{H^{\pm \pm}} \simeq 301 (227) \text{ GeV}$ for $v_\chi = 1000(1500) \text{ GeV}$, therefore we have it not taken into account.

In respect to the backscattered photons (Fig. 5 and 6); the statistics are the following. Taking $m_{H^{\pm \pm}} = 500 (700) \text{ GeV}$ and $v_\chi = 1000 \text{ GeV}$ we will have a total of $\simeq 4.5 \times 10^4 (2.9 \times 10^3) (\simeq 8.7 \times 10^4 (3.2 \times 10^4))$ events of $H^{\pm \pm}E^\mp$ produced per year. Regarding the VEV $v_\chi = 1500 \text{ GeV}$ and for the same $m_{H^{\pm \pm}} = 500 (700) \text{ GeV}$ it will give a total of $\simeq 4.4 \times 10^4 (7.8 \times 10^2 (\simeq 9.9 \times 10^4 (3.4 \times 10^4))$ events per year to produce $H^{\pm \pm}E^\mp$. So, we have that for the ILC the number of events is sufficiently appreciable for both bremsstrahlung photons and backscattering photons, therefore our analysis will concentrate on the both distributions.

We are going to consider the following two promising types of signals. The first, where we consider the decay of $H^{\pm \pm}$ into two leptons pairs $e^\pm E^\pm$, taking into account that the branching ratios for these particles would be $BR(H^{\pm \pm} \rightarrow e^\pm E^\pm) = 9.1 \times 10^{-1} \% (2.2 \times 10^{-1} \%)$ (Fig. 7), we would have approximately $\simeq 16 (0.22) (\simeq 52 (3))$ events per year for bremsstrahlung photons, for $m_{H^{\pm \pm}} = 500 (700) \text{ GeV}$, and $v_\chi = 1000 \text{ GeV}$ considering that the first two numbers of events ($\simeq 16 (0.22)$) correspond to 1.0 TeV and the other two ($\simeq 52 (3)$) to 1.5 TeV for the ILC respectively. Regarding the $v_\chi = 1500 \text{ GeV}$ for the same masses of $H^{\pm \pm} = 500 (700) \text{ GeV}$ and considering $BR(H^{\pm \pm} \rightarrow e^\pm E^\pm) = 37.8 \% (3.9 \%)$ (Fig. 8) it will give a total of $\simeq 6 \times 10^2 (2) (\simeq 2.2 \times 10^3 (51))$ events per year.

In respect to the backscattered photons the statistics are the following. Taking $m_{H^{\pm \pm}} = 500 (700) \text{ GeV}$ and $v_\chi = 1000 \text{ GeV}$ and considering the same decay given above, for which branching ratios would be $BR(H^{\pm \pm} \rightarrow e^\pm E^\mp) = 9.1 \times 10^{-1} \% (2.2 \times 10^{-1} \%)$, then we would have a total of $\simeq 410 (6) (\simeq 791 (70))$ events per year. For $v_\chi = 1500 \text{ GeV}$ and for $BR(H^{\pm \pm} \rightarrow e^\pm E^\pm) = 37.8 \% (3.9 \%)$, for the same $m_{H^{\pm \pm}} = 500 (700) \text{ GeV}$, we would have a total of $\simeq 1.7 \times 10^4 (30) (\simeq 3.7 \times 10^4 (1.3 \times 10^3))$ events per year.
TABLE IV: Results for the ILC considering decay modes for $H^{\pm\pm} \rightarrow e^\pm E^\pm$. WW and BL stands for bremsstrahlung photons using the Weizsäcker-Williams distribution and backscattered laser photons, respectively, where the first two numbers of Events/year correspond to 1.0 TeV and the other two to 1.5 TeV for the ILC.

| $v_\chi$ (GeV) | $m_{H^{\pm\pm}}$ (GeV) | BR($H^{\pm\pm} \rightarrow e^\pm E^\pm$) | Events/year | Mechanism |
|---------------|-------------------------|-----------------------------------|-------------|-----------|
| 1000          | 500 (700)               | 9.1 (2.2) $\times 10^{-1}$ %      | 16 (0.22) (52 (3)) | WW        |
| 1500          | 500 (700)               | 37.8 (3.9) %                      | 600 (2) (2200 (51)) |            |
| 1000          |                        | 9.1 (2.2) $\times 10^{-1}$ %      | 410 (64) (791 (70)) | BL        |
| 1500          |                        | 37.8 (3.9) %                      | 17000 (30) (37000 (1300)) |            |

TABLE V: Results for the ILC considering decay modes for $H^{\pm\pm} \rightarrow U^{\pm\pm}\gamma$ and $U^{\pm\pm} \rightarrow e^\pm E^\pm$. WW and BL stands for bremsstrahlung photons using the Weizsäcker-Williams distribution and backscattered laser photons, respectively, where as above the first two numbers of Events/year correspond to 1.0 TeV and the other two to 1.5 TeV for the ILC.

| $v_\chi$ (GeV) | $m_{H^{\pm\pm}}$ (GeV) | BR($H^{\pm\pm} \rightarrow U^{\pm\pm}\gamma$) | BR($U^{\pm\pm} \rightarrow e^\pm E^\pm$) | Events/year | Mechanism |
|---------------|-------------------------|-----------------------------------|-----------------------------|-------------|-----------|
| 1000          | 500 (700)               | 47.9 (21.9) %         | 50 (47.5) % | 431 (10) (1400 (140)) | WW        |
| 1500          |                        | 0.0 (41.4) %          | 0.0 (47.2) % | 0.0 (10) (0.0 (250)) |            |
| 1000          |                        | 47.9 (21.9) %         | 50 (47.5) % | 11000 (300) (21000 (3300)) |            |
| 1500          |                        | 0.0 (41.4) %          | 0.0 (47.2) % | 0.0 (152) (0.0 (6600)) | BL        |

Considering that the second signal for $H^{\pm\pm}$ are $U^{\pm\pm}\gamma$ and taking into account that the BRs for these particles would be BR($H^{\pm\pm} \rightarrow U^{\pm\pm}\gamma$) = 47.9 % (21.9 %) (Fig. 7) for $m_{H^{\pm\pm}} = 500 (700)$ GeV, $v_\chi = 1000$ GeV and that $U^{\pm\pm}$ decay into $e^\pm E^\pm$, whose BR($U^{\pm\pm} \rightarrow e^\pm E^\pm$) = 50 % (47.5 %) see Fig. 9 and [16], then we would have approximately $\simeq 431 (10)$ ($\simeq 1.4 \times 10^3 (1.4 \times 10^2)$) events per year for bremsstrahlung photons, considering as above that the first two numbers of events ($\simeq 431 (10)$) correspond to 1.0 TeV and the other two ($\simeq 1.4 \times 10^3 (1.4 \times 10^2)$) to 1.5 TeV for the ILC. Regarding $v_\chi = 1500$ GeV it will not give any event for $m_{H^{\pm\pm}} = 500$ GeV because it its restricted by the values of $m_U$ which in this case give 691.8 GeV (Table II). Taking the BR($H^{\pm\pm} \rightarrow U^{\pm\pm}\gamma$) = 41.4 % (Fig. 7), and BR($U^{\pm\pm} \rightarrow e^\pm E^\pm$) = 47.2 % see Fig. 10 and [16], for the mass of Higgs equal to $m_{H^{\pm\pm}} = 700$ GeV and the same $v_\chi$ then we have for the number of events per year a total of $\simeq 10$ ($\simeq 2.5 \times 10^2$) given that the first one number of events ($\simeq 10$) correspond to 1.0 TeV and the other ($\simeq 2.5 \times 10^2$) to 1.5 TeV for the ILC. Considering the backscattered
photons, and taking into account that the $\text{BR}(H^{\pm\pm} \to U^{\pm\pm}\gamma) = 47.9\%\ (21.9\%)$ (Fig. 7) and $\text{BR}(U^{\pm\pm} \to e^\pm E^\pm) = 50\%\ (47.5\%)$ (Fig. 9 and 16), then the number of events per year will be $\simeq 1.1 \times 10^4 (3 \times 10^2) (\simeq 2.1 \times 10^4 (3.3 \times 10^3))$, for the masses of the Higgs boson $m_{H^{\pm\pm}} = 500\ (700)$ GeV and $v_\chi = 1000$ GeV. Regarding $v_\chi = 1500$ GeV, it will not give any event for $m_{H^{\pm\pm}} = 500$ GeV because the same reasons given above. Considering the same branching ratios as above, that is $\text{BR}(H^{\pm\pm} \to U^{\pm\pm}\gamma) = 41.4\%$ (Fig. 7), and $\text{BR}(U^{\pm\pm} \to e^\pm E^\pm) = 47.2\%$ (Fig. 10 and 16) for the mass of Higgs equal to $m_{H^{\pm\pm}} = 700$ GeV and the same $v_\chi$ then the number of events per year will be $\simeq 152\ (\simeq 6.6 \times 10^3)$. All these results are resumed in Table IV and Table V.

B. CLIC Events

Considering that the expected integrated luminosity for the CLIC will be of the order of $3 \times 10^6$ pb$^{-1}$/yr. Then the statistics we are expecting for this collider for bremsstrahlung distribution (Fig. 11) are a total of $\simeq 9.9 \times 10^4 (\simeq 3.9 \times 10^4)$ of $H^{\pm\pm}$ and $E^\pm$ particles produced per year if we take the mass of the boson $m_{H^{\pm\pm}} = 500\ (700)$ GeV and $v_\chi = 1000$ GeV. In respect to the $v_\chi = 1500$ GeV for the same $m_{H^{\pm\pm}} = 500\ (700)$ GeV it will give a total of $\simeq 1.1 \times 10^5 (\simeq 4.2 \times 10^4)$ events per year to produce the same particles.

Taking the same types of signals as above, that is, $\text{BR}(H^{\pm\pm} \to e^\pm E^\pm) = 9.1 \times 10^{-1}\%\ (2.2 \times 10^{-1}\%)$ (Fig. 7), we would have approximately $\simeq 9 \times 10^2 (\simeq 86)$ events per year for $m_{H^{\pm\pm}} = 500\ (700)$ GeV and $v_\chi = 1000$ GeV. Regarding $v_\chi = 1500$ GeV and considering the same parameter as above and taking $\text{BR}(H^{\pm\pm} \to e^\pm E^\pm) = 37.8\%\ (3.9\%)$ (Fig. 8) then we would have $\simeq 4.2 \times 10^4 (\simeq 1.6 \times 10^3)$ events per year, for $m_{H^{\pm\pm}} = 500\ (700)$ GeV. For the second signal, considering $m_{H^{\pm\pm}} = 500\ (700)$ and $v_\chi = 1000$ GeV, for which $\text{BR}(H^{\pm\pm} \to U^{\pm\pm}\gamma) = 47.9\%\ (21.9\%)$ (see Fig. 7) and $\text{BR}(U^{\pm\pm} \to e^\pm E^\pm) = 50\%\ (47.5\%)$ (Fig. 9 and 16), it will give $\simeq 1.8 \times 10^4 (\simeq 4.1 \times 10^3)$ events per year, for bremsstrahlung photons. In respect to $v_\chi = 1500$ GeV, it will not give any event due to the same considerations given above, except in the case of $m_{H^{\pm\pm}} = 700$ GeV, which branching ratios are $\text{BR}(H^{\pm\pm} \to U^{\pm\pm}\gamma) = 41.4\%$ (Fig. 7), and $\text{BR}(U^{\pm\pm} \to e^\pm E^\pm) = 47.2\%$ (Fig. 10 and 16) for $m_{H^{\pm\pm}} = 700$ GeV and the same $v_\chi$, then the number of events per year will be $\simeq 8.2 \times 10^3$. All these results are resumed in Table VI and Table VII.
TABLE VI: The same as in Table V but for the CLIC collider.

| $v_{\chi}$ (GeV) | $m_{H^{\pm\pm}}$ (GeV) | $\text{BR}(H^{\pm\pm} \rightarrow e^{\pm}E^{\pm})$ | Events/year | Mechanism |
|------------------|-------------------------|----------------------------------|-------------|-----------|
| 1000             | 500 (700)               | $9.1 (2.2) \times 10^{-1}$ %    | $9.2 \times 10^2$ (86) | WW        |
| 1500             | 500 (700)               | $37.8 (3.9)$ %                  | $42 (1.6) \times 10^3$ |           |
| 1000             | 500 (700)               | $9.1 (2.2) \times 10^{-1}$ %    | $46 (7.2) \times 10^2$ |           |
| 1500             | 500 (700)               | $37.8 (3.9)$ %                  | $22 (1.5) \times 10^4$ | BL        |

TABLE VII: The same as in Table VI but for the CLIC collider.

| $v_{\chi}$ (GeV) | $m_{H^{\pm\pm}}$ (GeV) | $\text{BR}(H^{\pm\pm} \rightarrow U^{\pm\pm} \gamma)$ | $\text{BR}(U^{\pm\pm} \rightarrow e^{\pm}E^{\pm})$ | Events/year | Mechanism |
|------------------|-------------------------|----------------------------------|----------------------------------|-------------|-----------|
| 1000             | 500 (700)               | $47.9 (21.9)$ %                  | $50 (47.5)$ %                    | $18 (4.1) \times 10^3$ | WW        |
| 1500             | 500 (700)               | $0.0 (41.4)$ %                   | $0.0 (47.2)$ %                   | $0.0 (8.2 \times 10^3)$ |           |
| 1000             | 500 (700)               | $47.9 (21.9)$ %                  | $50 (47.5)$ %                    | $13 (3.4) \times 10^4$ |           |
| 1500             | 500 (700)               | $0.0 (41.4)$ %                   | $0.0 (47.2)$ %                   | $0.0 (7.6 \times 10^4)$ | BL        |

Referring to the backscattered photons (Fig. 12), considering $m_{H^{\pm\pm}} = 500 (700)$ GeV and $v_{\chi} = 1000$ GeV, we will have a total of $\simeq 5.1 \times 10^5 (3.3 \times 10^5)$ events of $H^{\pm\pm}E^{\mp}$ produced per year. Regarding $v_{\chi} = 1500$ GeV and for the same masses above it will give a total of $\simeq 5.7 \times 10^5 (3.9 \times 10^5)$ events per year to produce $H^{\pm\pm}E^{\mp}$. Taking the $m_{H^{\pm\pm}} = 500 (700)$ GeV and $v_{\chi} = 1000$ GeV and taking the same first signal as above, that is, $\text{BR}(H^{\pm\pm} \rightarrow e^{\pm}E^{\pm}) = 9.1 \times 10^{-1} \% (2.2 \times 10^{-1} \%)$ (Fig. 7) we will have a total of $\simeq 4.6 \times 10^3 (7.2 \times 10^2)$ events per year. With respect to $v_{\chi} = 1500$ GeV, and $m_{H^{\pm\pm}} = 500 (700)$ GeV, and considering now $\text{BR}(H^{\pm\pm} \rightarrow e^{\pm}E^{\pm}) = 37.8 \% (3.9 \%)$ (Fig. 8) it will give a total of $\simeq 2.2 \times 10^5 (1.5 \times 10^4)$ events per year. Considering the second signal for $m_{H^{\pm\pm}} = 500 (700)$ GeV and $v_{\chi} = 1000$ GeV and taking into account that $\text{BR}(H^{\pm\pm} \rightarrow U^{\pm\pm} \gamma) = 49.9 \% (21.9 \%)$ (Fig. 7), and $\text{BR}(U^{\pm\pm} \rightarrow e^{\pm}E^{\pm}) = 50 \% (47.5 \%)$ (Fig. 9 and [16]), we would have $\simeq 1.3 \times 10^5 (3.4 \times 10^4)$ events per year. Considering $v_{\chi} = 1500$ GeV it will not given any event for $m_{H^{\pm\pm}} = 500$ for the same reasons given above. For $m_{H^{\pm\pm}} = 700$ it presents $7.6 \times 10^4$ events per year regarding the branching ratios $\text{BR}(H^{\pm\pm} \rightarrow U^{\pm\pm} \gamma) = 41.4 \%$ (Fig. 7) and $\text{BR}(U^{\pm\pm} \rightarrow e^{\pm}E^{\pm}) = 47.2 \%$ (Fig 10 and [16]). All these results are resumed in Table VI and Table VII.
In this way we have as a signal for the process $e^\mp \gamma \rightarrow H^\mp E^\pm \rightarrow e^\mp E^\mp E^\pm$, this final state can be considered as the golden mode of decay. The background which can appear is $e^-\gamma \rightarrow e^- \rightarrow Ze^- \rightarrow e^- e^- e^-$, but these backgrounds can be readily reduced by imposing the Z window cut where the invariant mass of opposite-sign lepton pairs must be far from the Z mass: $|m_{e^\mp E^\pm} - m_Z| > 10$ GeV, this removes events where the leptons come from the Z decay [18].

These two charged leptons $e^\mp E^\pm$ are relatively easy to measure in the detector, as they leave tracks and do not shower like gluons and quarks, by computing the invariant masses of both the pairs. On the other side the signal of a process $E^\pm H^\mp \rightarrow E^\pm U^\mp \gamma$ and $U^\mp \rightarrow e^\mp E^\pm$, are $E^\pm e^\mp E^\mp \gamma$, where the $\gamma$ and $E^\pm$ will be measured with high accuracy by the detector and a sharp doubly charged gauge bosons will be observed in the two same-sign lepton invariant mass distribution. If we see this signal we will not only be seeing the DCHBs but also the doubly charged gauge bosons and heavy leptons. So the $e^\pm \gamma$ collisions can be also a plentiful source of DCHBs.

The discovery of DCHBs will be without any doubt of great importance for the physics beyond the SM because of the confirmation of the Higgs triplet representation and the verification of the existence of some exotic particles.

In summary, through this work, we have shown that in the context of the 3-3-1 Model the signatures for DCHBs can be significant for $e^\pm \gamma$ collisions obtained by bremsstrahlung and backward Compton scattering of laser. This kind of new particles have distinct experimental signals of like-sign dileptons, offering excellent potential for DCHBs discovery. Their observation in future high energy collider experiments would be a clear evidence of new physics. Thus, searching for $H^{\mp \pm}$ is one of the main goals of current and future high energy collider experiments. Our study indicates the possibility of obtaining a clear signal of these new particles with a satisfactory number of events.

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\[ \gamma \quad H^{--} \quad H^{--} \]

\[ e^- \quad E^+ \quad e^- \quad E^+ \]

(a) (b)
$e^\pm \gamma \rightarrow H^{\pm \pm} E^\mp$

$\sqrt{s} = 1.0 \text{ TeV}$

$\sigma (\text{pb})$

$M_{H^{\pm \pm}} (\text{GeV})$
$e^{\pm} \gamma \rightarrow H^{\pm} \ E^{\mp}$

$\sqrt{s} = 1.5 \ TeV$

$\sigma \ (pb)$

$v_\chi = 1 \ TeV$

$v_\chi = 1.5 \ TeV$

$M_{H^{\pm \pm}} \ (GeV)$
$e^\pm \gamma \rightarrow H^{\pm} E^{\mp}$

$\sqrt{s} = 1.0 \text{ TeV}$

- $\nu_X = 1.0 \text{ TeV}$
- $\nu_X = 1.5 \text{ TeV}$
$e^\pm \gamma \rightarrow H^{\pm} E^\mp$

$\sqrt{s} = 1.5 \text{ TeV}$
$\nu_{\chi} = 1 \, \text{TeV}$
\[ \nu_\chi = 1.5 \text{ TeV} \]
$\nu_{\chi} = 1 \text{ TeV}$
$\nu_\chi = 1.5 \text{ TeV}$
$e^\pm \gamma \rightarrow H^{\pm\pm} E^\mp$

$\sqrt{s} = 3 \text{ TeV}$

$\sigma \ (pb)$

$v_\chi = 1 \text{ TeV}$

$v_\chi = 1.5 \text{ TeV}$
\[ e^\pm \gamma \rightarrow H^{\pm\pm} E^\mp \]

\[ \sqrt{s} = 3 \text{ TeV} \]

\[ \sigma \text{ (pb)} \]

- \( \nu_\chi = 1 \text{ TeV} \)
- \( \nu_\chi = 1.5 \text{ TeV} \)

\[ m_{H^{\pm\pm}} \text{ (GeV)} \]